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Carbon Dioxide and Ozone in High School Classrooms

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Carbon Dioxide and Ozone in High School Classrooms

by

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Abstract

Carbon Dioxide and Ozone in High School Classrooms

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High school classrooms are important places of learning and working for millions of students and teachers. Because small discomforts can cause losses in student productivity and achievement, ensuring a healthy working environment is vital. As the primary method of supplying outdoor air to classrooms, mechanical ventilation systems are an important component of the indoor space and have the power to affect concentrations of indoor pollutants. The objective of this research was to investigate mechanical ventilation systems and the concentrations of two specific indoor pollutants, carbon dioxide and ozone, in high school classrooms. As part of this study, a two-year field researching campaign was conducted in seven high schools. Carbon dioxide concentrations were measured in the supply airstream and the general room area of classrooms. Through use of steady-state and dynamic mass balance analyses, classroom ventilation rates were estimated. Ozone concentrations were monitored on school rooftops and in classrooms to investigate the influence of mechanical system operation on ozone concentrations indoors. Mechanical ventilation systems were found to be an

important consideration when studying the indoor environment, with system operation affecting indoor carbon dioxide and ozone concentrations. When compared to the outdoor air recommendations provided by the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) in Standard 62.1, it was found that many classrooms did not receive sufficient fresh air. Classrooms located in portable structures were found to receive large amounts of outdoor air through infiltration and natural ventilation when compared to classrooms in permanent structures. A relationship between average carbon dioxide concentrations and indoor-to-outdoor ozone concentrations was observed, indicating the influence of outdoor air on the concentrations of both pollutants indoors.

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EXECUTIVE SUMMARY

Chapter 1: Introduction

In this chapter, the issue and potential impacts of poor air quality in high school classrooms are explained. The objectives and scope of the research are stated, and a brief outline of this thesis is provided.

1.1 THE ISSUE

As the largest public enterprise in the United States, primary and secondary schools constitute an important environment for millions of students and teachers who spend their days in classrooms (GAO, 1995). High school students, in particular, spend approximately 1,195 hours per year in school where they are expected to learn and work productively ("Public School Data File", 2008). In these environments, minor discomforts in environmental quality can translate to major losses in student productivity, health, academic achievement, and attendance (Shendell et al., 2004; Jones et al., 2007; Jones, et al., 2010; Almeida et al., 2011; Lin et al., 2012; Haverinen-Shaughnessy et al., 2015). Schools are often faced with insufficient budgets and sometimes opt to reduce ventilation for the purpose of energy savings (USEPA, 2017). As the source of fresh (outdoor) air in most school environments and, thus, the primary method of dispelling indoor pollutants, mechanical ventilation systems are paramount to the environmental quality in classrooms (Annesi-Maesano et al., 2013; Daisey et al., 2003).

Despite the importance of classroom environments, relatively few studies have been conducted exclusively on high schools, and fewer still have been conducted in the hot, humid climate of central Texas. Additional information about the influence of mechanical ventilation system operation on learning in high school environments can help inform school district officials and lead to improvements in student performance.

1.2 Objectives

There were several goals of the two-year field researching campaign and subsequent analysis with respect to ventilation, carbon dioxide (CO_2), and ozone. The objectives of this study were: (1) collect information about types of mechanical ventilation systems and ventilation rates in a variety of classroom environments, (2) assess CO_2 concentrations in classrooms during both occupied and unoccupied periods, and (3) gather classroom and ambient ozone concentration to compare with ventilation and CO_2 information.

1.3 Scope of Research

The research presented in this document is a subset taken from a larger field study entitled the Healthy High School PRIDE (Partnership in Research on InDoor Environments) study. The Healthy High School PRIDE study is ongoing at seven high schools in central Texas, and it aims to determine information about indoor pollutants in classrooms. Included in this four-year study was a two-year field research component, in which thirty classrooms were sampled for four consecutive school days four separate times. The information presented in this document includes the types and operation of mechanical ventilation systems used in each school and the field results related to CO_2 and ozone concentrations.

1.4 Outline of Thesis

The background section (Chapter 2) of this thesis summarizes previous research on relationships between mechanical ventilation, CO_2, and ozone, and the impact on student achievement. Methods used to gather data throughout the field research are described in Chapter 3. Major findings from the field study related to mechanical ventilation, CO_2, and ozone are summarized in Chapter 4. Conclusions and recommendations for future research are presented in Chapter 5.

This M.S. research produced two papers, and they are attached as appendices to this summary. A paper accepted for publication in *ASHRAE Transactions* (*Ventilation and Corresponding CO_2 Levels in High School Classrooms*) is provided in Appendix A. Another paper, which will be submitted for journal publication, is attached in Appendix B and is entitled *Ozone Concentrations in High School Classrooms*. These papers can be referenced to obtain more detail about the study and conclusions.

Chapter 2: Background

This chapter aims to provide background information about ventilation, carbon dioxide (CO_2), and ozone. General information about the history of ventilation and its place in schools is provided. The use of CO_2 to determine ventilation characteristics is explained, and scientific findings related to CO_2 and ventilation are outlined. The detrimental health effects of ozone and its reaction products are explored, and research findings related to atmospheric and indoor ozone concentrations are provided.

2.1 Ventilation and Carbon Dioxide

Ventilation in indoor spaces has been considered for centuries, with examples of designs to optimize ventilation seen in early societies (Janssen, 1999; Matson and Sherman, 2004). Ancient Egyptians recognized higher incidences of respiratory distress due to dust exposure in stone carvers working indoors when compared to those outdoors (Janssen, 1999). Banpo villagers in China developed chimneys for homes as early as 4000-5000 B.C. (Matson and Sherman, 2004). As societies progressed, more experience lead to greater emphasis on ventilation and indoor environmental quality. An example of a building regulation for ventilation can be found in 1631 A.D., when King Charles I of England required that homes be higher than ten feet and a window's height be greater than its width to maximize natural ventilation (Matson and Sherman, 2004).

The effects of airflow through indoor spaces were researched and reported as early as the 18th century (Klauss et al., 1970; Persily, 2015). Though early researchers struggled to identify sources and causes of poor environmental quality indoors, they realized ventilation could minimize "bad air" (Klauss et al., 1970; Janssen, 1999; Persily, 2015). In 1913, The New York State Ventilation Commission reduced the minimum per-

person ventilation recommendation of 15 L/s to 8 L/s in schools and public buildings (Persily, 2015). This reduced airflow rate was not based on health guidelines, but chosen because 8 L/s per person was sufficient to minimize body odors (Persily, 2015).

The general standard of 8 L/s per person remained relatively unchanged for many years. The first standard published by the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) listed the minimum acceptable ventilation rate for classrooms as 5 L/s per person, with a recommendation of 5– 7.5 L/s per person in Standard 62-1973 (ASHRAE, 1973; Persily, 2015). Though subsequent versions of ASHRAE Standard 62 updated some information, the ventilation requirement for classrooms remained relatively constant, with a minimum per-person ventilation recommendation of 8 L/s listed in ASHRAE Standard 62-1989 (ASHRAE, 1989; Persily, 2015).

In 2004, Standard 62.1 changed the format for determining the minimum acceptable fresh air flowrate from a fixed amount based on occupancy levels to a two-part approach based on both occupancy and floor area (ASHRAE, 2004; Persily, 2015). In Standard 62.1-2004, the minimum fresh air requirement for classrooms was 8 L/s per person, while larger classrooms such as lecture halls were given a minimum fresh air recommendation of 4 L/s per person (ASHRAE, 2004; Persily 2015). In the most recent version of Standard 62.1, published in 2016, the minimum recommendation for classrooms and lecture halls is listed as 5 L/s and 3.8 L/s per person, respectively (ASHRAE, 2016). Though the most recent per-person ventilation rates are lower than previous standard recommendations, a similar overall rate results when accounting for the floor area airflow requirement.

The recommendations provided by ASHRAE Standard 62.1 serve only as guidelines for architects and facility operators. Often, energy-saving strategies such as minimizing fresh airflow or reducing operational time for mechanical systems are employed by building operators (Laverge et al., 2011). As described in Appendix A, sacrifices in ventilation, specifically the supply of fresh air, were found to be made in portable classrooms in central Texas in order to ensure thermal comfort for occupants (Lesnick et al., 2017).

Carbon dioxide is an important gas to consider when evaluating indoor air quality and ventilation. Carbon dioxide is a useful tracer gas when estimating ventilation indoors because of the ability to estimate human production rates of CO_2, its known concentration in the atmosphere, and its unreactive nature (Persily, 1997; ASTM 2012). Ventilation rates may be determined through both dynamic and steady-state mass balance analyses of CO_2 concentrations in a closed control volume (ASTM, 2012; Persily, 1997).

In addition to estimating specific ventilation rates, analysis of CO_2 concentrations can provide insight into the general air quality of an indoor space. High CO_2 levels have been associated with health symptoms (Simoni et al., 2010; Annesi-Maesano et al., 2013). Carbon dioxide concentrations can also be related to the risk of transmission of airborne infectious diseases using the rebreathed fraction (RF) as a screening model (Rudnick and Milton, 2003).

Ventilation rates have been examined and characterized in schools through direct methods such as flow hood measurements and indirect measurement methods such as CO_2 concentration analysis (Daisey et al., 2003). Poor ventilation in schools has been shown to create uncomfortable thermal conditions and a buildup of indoor pollutants

(Ramalho et al., 2015). High CO_2 concentrations, indicative of inadequate ventilation, have also been shown to increase the risk of the transmission of airborne diseases such as the cold and flu (Rudnick and Milton, 2003). Increased ventilation has been associated with decreased student absenteeism (Shendell et al., 2004; Gaihre et al., 2013). Additionally, recent studies have found that increased ventilation can positively affect student achievement and academic performance (Haverinen-Shaughnessy et al., 2011; Haverinen-Shaughnessy et al., 2015; Mendell et al., 2015).

2.2 Ozone

Ozone is a typically outdoor-originating compound that has significant health implications for children and adults. Exposure to ozone has been associated with a multitude of health effects, including: respiratory illness and distress (Mudway and Kelly, 2004; USEPA, 2006a), decreased pulmonary function (USEPA, 2006a; Brown et al., 2008), and increased risk of mortality (Thurston and Ito, 2001). The risk of emergency room visits related to one particular respiratory illness, asthma, was found to increase with increasing ambient ozone concentrations (McDonnell et al., 1999; Glad et al., 2012). Ozone has also been shown to adversely affect the health of children. Tager et al. (2005) associated decreased airway function with increased ozone exposure during childhood. Additionally, increased ozone exposure has been linked to increased cases of asthma in children, especially those who spend extended time outdoors (McConnell et al., 2002).

Because the outdoor atmosphere is generally the greatest source of ozone indoors, the indoor concentration of ozone is to some extent a function of mechanical ventilation (Weschler et al., 1989; Lai et al., 2015). Indoor ozone concentrations also depend to some extent on natural ventilation, such as opening doors or windows and infiltration

(Stephens et al., 2011; Lai et al., 2015). Studies have shown that indoor exposure to ozone may be significant and potentially more harmful than outdoor exposures (Weschler et al., 1989; Chen et al., 2012). Though the greatest source of ozone indoors is generally ambient air, devices such as photocopy machines, laser printers, air cleaners, and other electronic equipment are known to generate ozone and can thus further increase indoor concentrations (Phillips and Jakober, 2006; Destaillats, et al., 2008; Zhang and Jenkins, 2016).

While ozone alone has been proven harmful for humans, exposure to indoor ozone is often joined by exposures to ozone-initiated reaction products (Li et al., 2002; Weschler, 2004; Weschler, 2006; Singer et al., 2006). These reaction products, which may be gaseous or particulate, originate from ozone reactions with unsaturated volatile organic compounds (VOCs) and can be irritating or toxic to occupants (Li et al., 2002; Weschler, 2004; Weschler, 2006). Because sources of VOCs include surfaces such as carpeting, fabric, and paint and chemicals found in cleaning supplies and air fresheners, reactions between ozone and VOCs can occur in large amounts indoors (Nazaroff and Weschler, 2004; Singer et al., 2006; Rim et al., 2016).

The presence and effects of ozone in schools have been studied to some extent. Morowska et al. (2009) found increased amounts of ultrafine particles, perhaps from ozone-initiated reactions, during periods of cleaning and art class. Reactions between ozone and the scenting agents of children's markers to form ultrafine particles have been shown to occur (Fung et al., 2014). Additionally, studies have found greater student absenteeism was liked to increased ambient ozone concentrations (Romieu et al., 1992; Gilliland, et al., 2001; Park et al., 2002).

The relationship between indoor ozone, ambient ozone, and mechanical ventilation is important when considering exposure implications for students. Because mechanical ventilation is used to supply most school buildings with fresh air and ambient air is often a large source of indoor ozone, there is a relationship between the operation of heating, ventilating, and air conditioning (HVAC) systems and indoor ozone concentrations (Lee et al., 1999). It is important for schools to meet or exceed the minimum fresh air ventilation requirements prescribed in ASHRAE Standard 62.1-2016 to prevent accumulation of harmful indoor pollutants. However, increasing the supply of fresh air can increase exposure to outdoor pollutants, such as ozone, and related reaction products (Yu et al., 2014).

While there are a significant number of studies that have investigated ozone in schools, there are still many questions to be answered. This is especially the case for the high-occupancy environments of high school classrooms. Additionally, these unique environments present a diversity of building types (permanent and portable structures), mechanical ventilation systems, and operation schedules that work together to impact indoor ozone concentrations.

Chapter 3: Methods

In this chapter, the methods for executing the field sampling experiments are outlined, including an overview of the study and the collection and analysis of carbon dioxide (CO_2) and ozone concentration data. Broad characteristics of the study, such as the dates and times of sampling periods, types of classrooms analyzed, and classroom characteristics are provided. The instrumentation used to collect CO_2 and ozone data is described, and a brief explanation of the theory behind calculations is provided.

3.1 Overview

The Healthy High School PRIDE study involved two years of field sampling in high school classrooms. Four specific periods of field sampling during the 2015-16 and 2016-17 school years were conducted. The first period was conducted in September, October, and November 2015 ("Fall 2015"), while the second took place during February and March 2016 ("Spring 2016"). In the second year of the study, sampling events were conducted in September, October, and November 2016 ("Fall 2016") and January, February, and March 2017 ("Spring 2017"). During the Fall 2015 and Spring 2016 sampling events, seven high schools were studied (denoted as EP1, EP2, EP3, EP4, EP5, EP6, and EP7 throughout this manuscript). During the Fall 2016 and Spring 2017, a subset of five high schools included in the same school district were studied (EP3, EP4, EP5, EP6, and EP7).

The schools chosen for this study are generally large in both area and enrollment. Six of seven schools studied (EP1, EP3, EP4, EP5, EP6, and EP7) enrolled more than 2,600 students in the 2015-16 school year. These schools are composed of expansive buildings with multiple large wings. In two schools studied (EP1 and EP5) multiple permanent buildings contain school classrooms. One school (EP2) is a small charter school located in a rented building in a light industrial development.

To capture daily variation of ventilation and indoor air quality, all sampling events lasted four full school days; the only exception is EP2 in Spring 2016, which lasted three full school days due to a school holiday. Instruments were deployed in classrooms on Monday afternoons after the end of the school day and left to monitor continuously until Friday afternoons after the completion of classes. Table 1 includes information about the time periods in which each school was monitored.

School	Start Date			
Code	Fall 2015	Spring 2016	Fall 2016	Spring 2017
EP1	09/28	03/07	-----	-----
EP2	09/21	03/21*	-----	-----
EP3	11/02	02/22	10/24	01/30
EP4	10/19	02/08	10/03	02/13
EP5	10/12	02/15	11/14	02/06
EP6	10/26	02/21	11/07	03/20
EP7	10/05	02/09	10/10	02/20

Table 1. Start dates of each sampling event.

Thirty classrooms were chosen to be monitored during each field sampling period. In general, the same classrooms were monitored in the first year of study (Fall 2015 and Spring 2016). In the second year of study, some new classrooms were chosen, while others from the first year were repeated. The majority of the classrooms were located in permanent structures (“permanent classrooms”). Various types of permanent classrooms were studied, including traditional rooms, laboratories, art studios, and woodworking shops. Some classrooms were located in nonpermanent, temporary structures (“portable classrooms" or "portables"). The portable classrooms studied were generally located on asphalt parking lots or grass fields adjacent to the school. The total number and type of classrooms studied at each school site throughout the entire field sampling campaign is summarized in Table 2.

	Classrooms Sampled							
School Code	Total	Traditional	Science Lab	Computer Lab	Art Studio	Wood Shop	Gym	Portable
EP1	4	3	1					
EP2	4	2	2					
EP3	7	1	2		1	1		2
EP4	6	2	1		1			2
EP5	7	1	3	1	1		1	
EP6	7	3	1	1				2
EP7	11	6	2	1				2
Total	46	18	12	3	3	1	1	8

Table 2. Types of classrooms studied.

Of the permanent classrooms studied, 27 were located on the exterior of the school buildings, and 11 were located in the core of the building. All permanent classrooms on the exterior of the building had inoperable (unable to open) windows. All permanent classrooms located in the core of the building did not have windows to the outdoors. All portable classrooms had operable windows and doors that immediately accessed outdoors.

3.2 VENTILATION AND CARBON DIOXIDE

Collaboration between school utility workers at one school district provided further information about mechanical ventilation systems and their operation in five of the seven schools (EP3, EP4, EP5, EP6 and EP7). At these five schools, the two main types of heating, ventilating, and air conditioning (HVAC) systems used to provide air to permanent classrooms are direct expansion units and variable-air-volume (VAV) units. Classrooms serviced by direct expansion units were all single zone, while classrooms serviced by VAV units were part of multizone systems. Portable classrooms in all five schools were serviced by single zone wall air conditioning (AC) units.

Runtime fractions were calculated for portable classrooms to determine the percentage of time that AC units were operational each day (Thornburg et al., 2003). Data about the types of HVAC systems, number of zones, and runtime fractions for some classrooms studied during the first year of field sampling can be found in Appendix A. More detail about HVAC system maintenance and operation can be found in the papers included in Appendices A and B.

To measure CO_2 concentrations, two CO_2 sensors (Telaire 7001, Onset Corporation, Bourne, MA) connected to data loggers (HOBO U12, Onset Corporation, Bourne, MA) were deployed in the supply airstream and general room area of each classroom. The CO_2 sensors have a measurement accuracy of ±50 ppm or 5% of the measurement (whichever is greater). The data loggers are able to record CO_2 concentrations of 2500 ppm or lower. The CO_2 sensors output concentration continuously, and the data loggers recorded the concentration every 30 seconds for the duration of the sampling period. Each CO_2 sensor was calibrated weekly prior to field sampling at a school site using atmospheric air. CO_2 sensors and data loggers were deployed in the supply airstream and room area of every classroom studied, although some data were lost due to instrumentation issues.

Carbon dioxide sensors and data loggers placed in the supply airstream were generally inserted into supply air ducts through ceiling diffusers. For cases in which the supply air was delivered via a side wall grill, the CO_2 sensor was secured to the outside of the grill. Carbon dioxide sensors and data loggers monitoring the general room concentrations were placed in muffle boxes with other instruments to minimize student or teacher interference. To minimize disruption to classes, the muffle boxes were generally placed on top of cabinets or counters on the edges of the classroom.

Daily and weekly average CO_2 concentrations were calculated during the occupied period of the school day. Peak CO_2 concentrations were also calculated. To minimize the influence of a single extreme reading when calculating peak CO_2 concentrations, data were first averaged in five-minute increments. Using average CO_2 concentrations, rebreathed fractions (RF) were calculated for each classroom during the occupied period to compare the relative risk of infection from an airborne sickness. When calculating the RF, the concentration of CO_2 on exhaled breath was assumed to be 38,000 ppm for all occupants (ASTM, 2012; ASHRAE, 2013). In all calculations, outdoor CO_2 concentrations were assumed to be 400 ppm based on representative measurements taken throughout the field sampling period.

Overnight fresh (outdoor) air exchange rates ("overnight AER_f", h^{-1}) during the unoccupied, nighttime period were calculated using a decay analysis (ASTM, 2012). Fresh air exchange rates ("AER_f", h^{-1}) were calculated during the occupied day period using a steady-state analysis with an assumed CO_2 generation rate of 0.31 L CO_2 per minute per occupant (Persily, 1997). All classrooms were assumed to be well-mixed. This assumption was supported by air flow rate measurements corresponding to overall air exchange rates (AER, h^{-1}) between 4 and 8 h^{-1} taken in representative classrooms during the occupied period throughout the entire field sampling campaign (Amai and Novoselac, 2016). Additional information about the methods used to estimate ventilation rates based on CO_2 concentrations can be found in Appendix A.

3.3 Ozone

Ozone concentrations were measured on the roof and in two or three classrooms at every school site. In one instance during Fall 2015, four classrooms in EP5 were monitored in addition to the roof. To measure ozone concentrations, single beam and dual beam UV absorbance ozone analyzers were used (2B Technologies, Boulder, CO). The ozone analyzers have a measurement accuracy of ± 1.5 ppb or 2% of the measurement (whichever is greater) and recorded the average ozone concentrations every five minutes continuously for each sampling event.

An ozone analyzer was stored inside a large, weather-resistant box and placed on top of each school roof during each sampling event. A sample tube was used to pull ambient air into the weather-resistant box to be analyzed. In general, the box containing the ozone analyzer was placed in an open area on the roof and an extension cord was used to power the analyzer. In some instances, ambient ozone concentration data from the roof analyzer were lost or only partially recorded due to loss of power. Ambient ozone concentrations recorded on each school roof were compared to data collected at Continuous Air Monitoring Stations (CAMS) operated by the Texas Commission of Environmental Quality (TCEQ).

Classroom ozone analyzers were placed inside muffle boxes, cases which have the purpose of dampening noise from instruments. To minimize disruption to classes, muffle boxes were generally placed on top of cabinets or counters towards the edges of the room. In general, the muffle boxes containing ozone analyzers was placed near the muffle box containing the CO_2 sensor and other instrumentation. In some instances, ozone concentration data for classrooms were lost due to loss of power to the ozone analyzer.

Daily and weekly average ozone concentrations during the occupied time were calculated. Peak ozone concentrations in each classroom were determined. Indoor-to-outdoor (I/O) ozone concentrations were calculated using ambient roof data throughout the entire sampling period in order to compare schools sampled at different time periods. More information about the collection and analysis of ozone concentration data can be found in Appendix B.

Chapter 4: Major Results

In this chapter, major results related to ventilation, carbon dioxide (CO_2), and ozone are presented. A brief discussion about the reasons for each result is included. More information about major results is included in the journal papers attached as Appendices A and B.

4.1 Ventilation and Carbon Dioxide

Ventilation was fully characterized in 22 of the 30 classrooms studied in Fall 2015 and Spring 2016. Two types of HVAC systems were found to provide air to permanent classrooms in the five schools for which more detailed information was known: Variable Air Volume (VAV) systems and Split Systems. All Split Systems were single-zone and provided conditioned air to a single classroom. All VAV Systems were multi-zone, and the number of zones serviced by a single air handling unit ranged from to 4 to 35. It was found that all portable classrooms studied used a single-zone wall air conditioning (AC) unit. Runtime fractions were calculated for portable classrooms in Fall 2015 and Spring 2016 using temperatures measured in the supply air and general room space (Thornburg et al., 2013). Runtime fractions ranged from 0.01 to 0.62 across all four sampling periods. More information about the types of systems, number of zones, and runtime fractions can be found in Appendix A.

Average CO_2 concentrations were calculated for the entire occupied period of each classroom in all sampling events (Figure 1). It was observed that average CO_2 levels were generally higher in the first year of field sampling (Fall 2015 and Spring 2016, Figure 1A) than in the second year (Fall 2016 and Spring 2017, Figure 1B). Evidence for this can be seen in the percentage of classrooms that had average CO_2

concentrations in compliance with the current guideline of 1100 ppm set by ASHRAE (ASHRAE, 2016). During the first year of field sampling (Figure 1A), 24% and 28% of classrooms in Fall 2015 and Spring 2016, respectively, had average CO_2 concentrations below the recommended maximum. During the second year of field sampling (Figure 1B), the number of classrooms in compliance with the provided ASHRAE recommendation increased to 57% and 46% in Fall 2016 and Spring 2017, respectively.

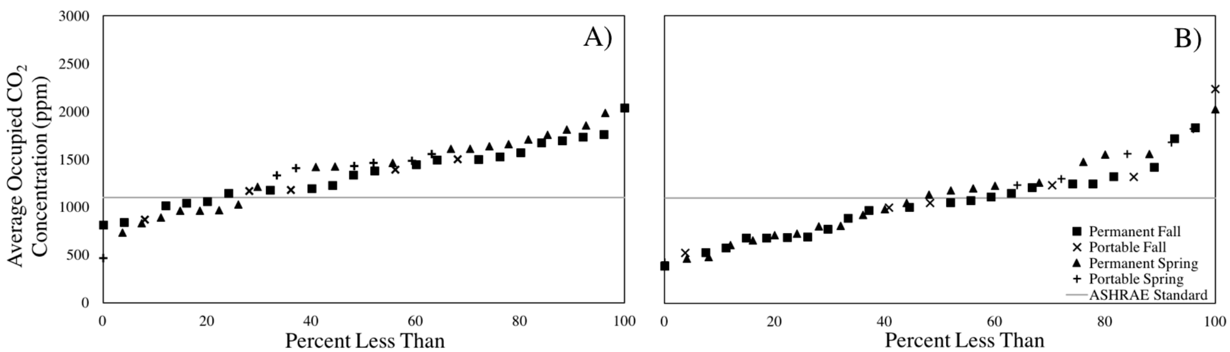

Figure 1: Average occupied carbon dioxide concentrations.

Peak CO_2 concentrations were also calculated for the entire occupied period of each classroom in all sampling events (Figure 2). Similar to average CO_2 concentrations, peak CO_2 concentrations were generally lower in the second year of field sampling (Figure 2B) when compared to the first year (Figure 2A). This is obvious when comparing the difference in the percentage of classrooms that had peak concentrations exceeding the maximum recommended CO_2 concentrations of 1100 ppm (ASHRAE, 2016). Whereas in both Fall 2015 and Spring 2016, one classroom displayed peak concentrations below the recommended maximum, the percentage of classrooms in Fall 2016 and Spring 2017 in compliance with this guideline was 25% and 31%, respectively (Figures 2A and 2B). Additionally, the number of classrooms that displayed the maximum possible reading for the instruments (2500 ppm) decreased between the first and second year. A combined total of 17 classrooms in Fall 2015 and Spring 2016 reached the maximum CO_2 concentration, whereas only nine classrooms during the Fall 2016 and Spring 2017 sampling periods hit this limit.

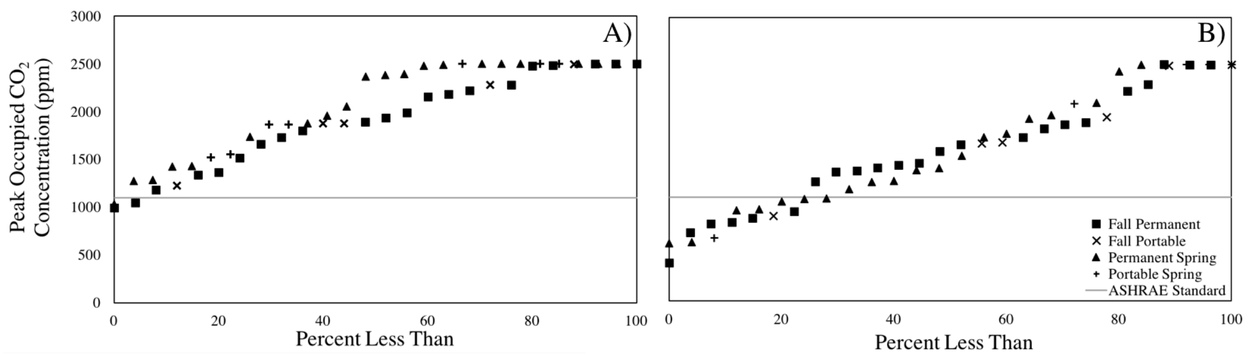

Figure 2: Peak occupied carbon dioxide concentrations.

Reasons for the decrease in classroom CO_2 concentration between the first and second years of field sampling could have stemmed from findings of the first year sampling effort. A presentation of findings from the first year of field sampling was given to the school district after the conclusion of the Spring 2016 field sampling campaign. In this presentation, the higher-than-recommended average CO_2 concentrations were emphasized, which may have lead district officials to change the operations and maintenance procedure for several air handling units.

Carbon dioxide concentrations were analyzed to characterize the ventilation in classrooms during Fall 2015 and Spring 2016 (Figure 3). Overnight AER_fs were found to be much more variable in portable classrooms when compared to permanent classrooms

(Figure 3A). Permanent classrooms studied in Fall 2015 and Spring 2016 had similar overall averages of 0.16 and 0.15 h^{-1}, respectively. Portable classrooms also had similar overnight AER_f values in Fall 2015 and Spring 2016, with overall averages of 0.79 and 0.70 h^{-1}, respectively. However, when all overnight AER_f values are compared between permanent and portable classrooms, portables display a much greater range. While overnight AER_f ranged from 0.03 to 0.40 h^{-1} in the first year of field sampling for permanent classrooms, portable classrooms had a much greater range of 0.11 to 1.35 h^{-1} during the same time period.

The AER_f values calculated for the occupied period displayed similar trends to those calculated for the overnight periods (Figure 3B). Permanent and portable classrooms had similar ventilation characteristics when compared to other classrooms of the same type. However, portable classrooms were much more variable when compared with permanent classrooms. While the range of occupied AER_fs for permanent classrooms was 0.72 to 4.78 h^{-1} in the first year of field sampling, the range of portable classrooms was 1.43 to 9.07 h^{-1} during the same time period.

Ventilation in the classrooms was compared to the specified ventilation provided by ASHRAE Standard 62.1-2016. For each classroom studied, the prescribed ventilation rate and corresponding AER_f value were calculated based on floor area and occupancy levels. These recommended AER_fs were averaged and are compared to the actual AER_fs calculated for the classrooms (the average recommended AER_f and one positive and negative standard deviation are shown in Figure 3B by solid and dashed lines). This comparison indicates that permanent classrooms do not receive the recommended amount of fresh air most of the time, while portable classrooms perform better.

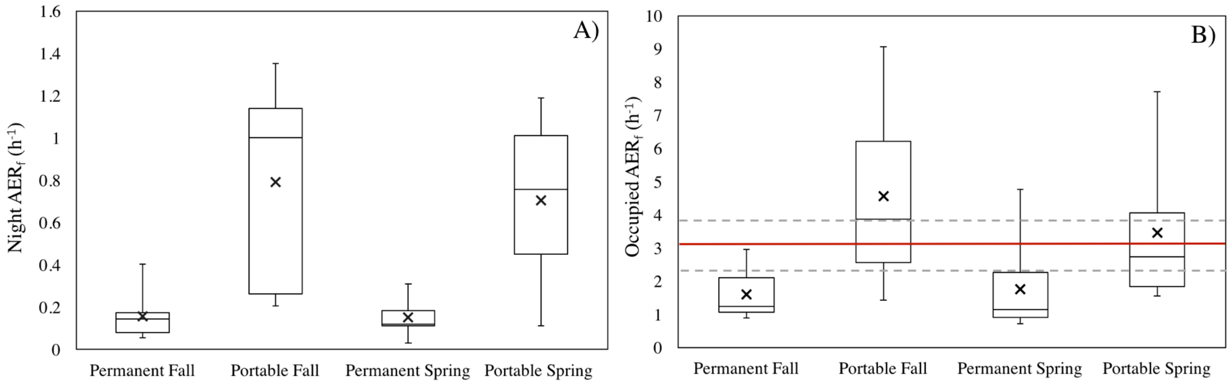

Figure 3: Average AER$_f$ during the overnight periods and occupied periods.

Portable classrooms are likely more variable than permanent classrooms for several reasons. While permanent buildings have tight building envelopes, portable structures are much “leakier”, leading to the infiltration of more fresh air from outdoors. This theory was further supported when manual inspection of the HVAC systems for portable classrooms revealed that, in all but one portable, the fresh air intake dampers were purposefully and permanently closed. Additionally, all portable classrooms studied had windows and doors that directly accessed the outdoors, while permanent classrooms did not. Because portable classrooms directly access the outdoor environment, the supply of fresh air was also affected by occupant behavior and preferences. Because teachers and students can open doors and windows to regulate the temperature in a portable classroom, higher AER$_f$ values were seen at times. Additional information about results relating to ventilation and CO_2 can be found in Appendix A.

4.2 Ozone

Weekly concentration profiles indicate close tracking between the measurements of ambient ozone made by the Texas Commission on Environmental Quality (TCEQ) at a

Continuous Air Monitoring Station (CAMS) and those taken on the roof of each school (Figure 4). This was true for all schools in the study. The ambient ozone concentrations measured on the roof or by the CAMS can be compared with the indoor concentrations in classrooms to demonstrate the influence of mechanical systems on the indoor environment. In general, the indoor concentration of ozone closely followed outdoor concentrations, although overall levels were lower due to reactions of ozone in the air handling units, supply ducts, and the classrooms.

Different permanent classrooms in the same school displayed different indoor ozone concentrations throughout the day. This is likely due to different operation of the HVAC systems supplying classrooms with fresh air. Although schools generally used the same type of HVAC system to condition permanent classrooms, the maintenance and operation of each specific air handling unit could have a large effect on the amount of fresh air and thus the amount of ozone supplied to each room.

Further influence of mechanical ventilation on indoor ozone concentrations is illustrated by the premature truncation of indoor ozone peaks when compared to ambient levels. Though the indoor and outdoor ozone concentrations generally increase and decrease synchronously, indoor ozone concentrations often decrease sharply at the end of the school day, prior to a decrease in the outdoor concentration. This decrease corresponds with the end of the school day, when mechanical systems are turned off and little fresh air flows to classrooms.

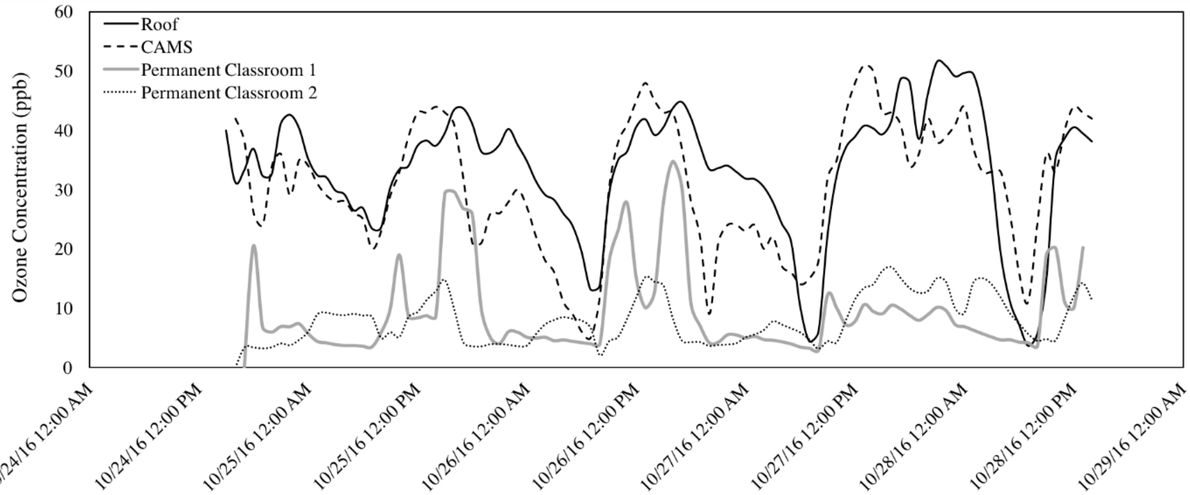

Figure 4: Sample weekly ozone concentration profile (Fall 2016)

Typically, portable classrooms displayed different indoor concentration profiles when compared to permanent classrooms (Figure 5). The indoor concentration of ozone in portable classrooms was generally higher than in permanent classrooms and more variable. This is likely due to higher fresh air exchange rates (AER_fs) in portable classrooms. Because more fresh air is provided to portable classrooms via infiltration and occupant behavior (e.g. opening doors and windows), higher ozone concentrations exist indoors.

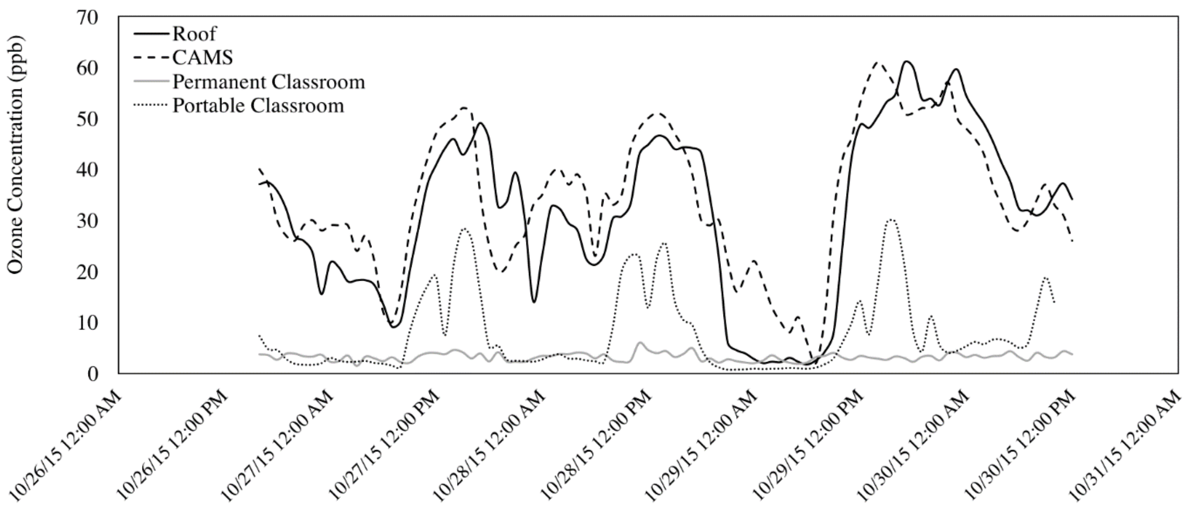

Figure 5: Sample weekly ozone concentration profile (Fall 2015)

To compare indoor ozone concentrations, indoor-to-outdoor (I/O) ozone ratios were calculated and presented as cumulative distribution plots for each sampling period (Figure 6). Typically, I/O ozone concentrations for a given classroom fell within the same range for all sampling periods. Though the I/O ozone concentrations measured in portable classrooms were generally slightly higher than those in permanent classrooms, portable classrooms still represented a wide range of the I/O spectrum.

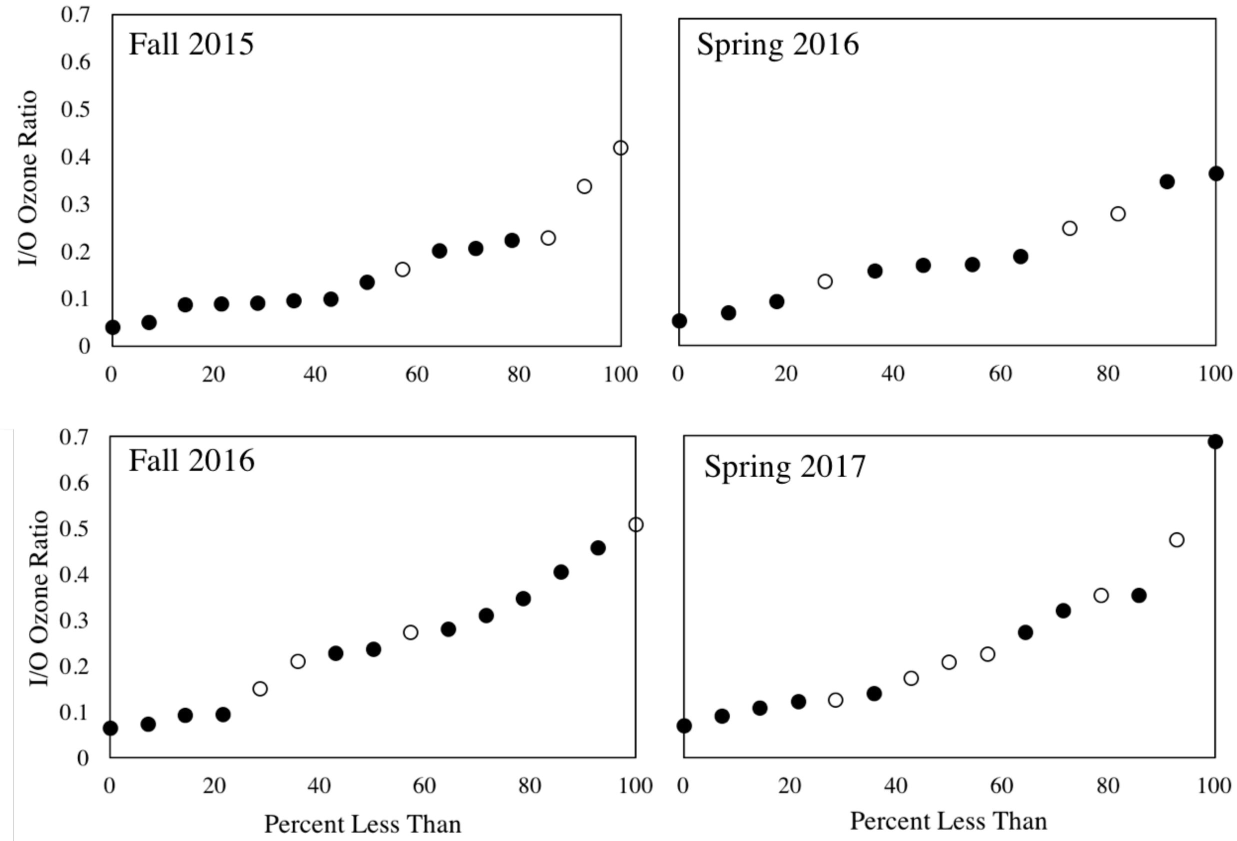

Figure 6: Cumulative distributions of average I/O ozone

When average CO_2 concentrations were compared to average I/O ozone concentrations, a clear trend was observed (Figure 7). When only I/O ozone concentrations above 0.1 were considered, a linear relationship with a slope of -0.0004 and an intercept of 0.68 was found in permanent classrooms (Figure 7A). When the same I/O ozone concentrations were considered in portable classrooms, a linear relationship with a slope of -0.0002 and an intercept of 0.51 was found (Figure 7B). Classrooms in which the I/O ozone concentration was below 0.1 were excluded due to uncertainty in the ozone measurement and a clear convergence of the data points with the x-axis.

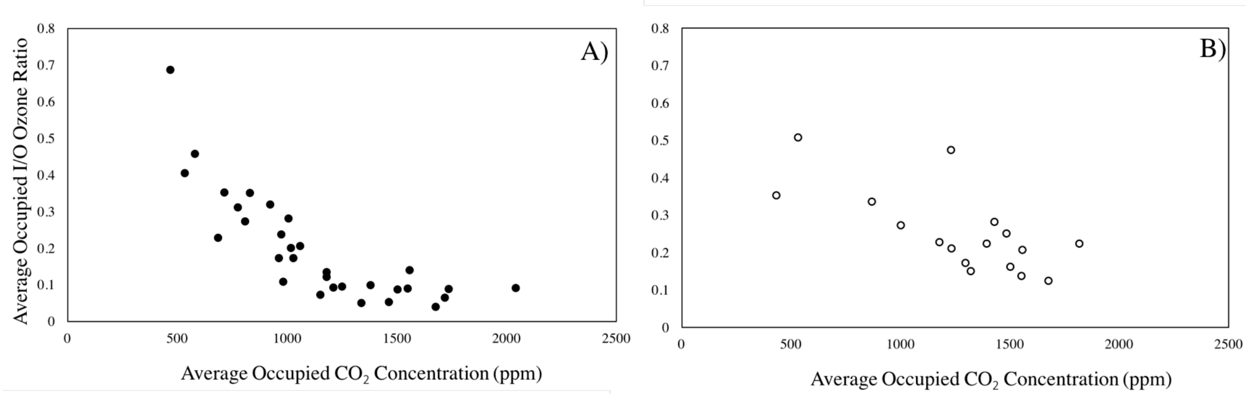

Figure 7: I/O ozone and average occupied CO_2 concentration

The relationship between ozone and CO_2 in permanent and portable classrooms can be explained by the supply of fresh air. As more fresh air is supplied to an indoor space, accumulated CO_2 concentrations will be diluted and exhausted, resulting in lower CO_2 levels. At the same time, fresh air often represents the largest source of ozone in the indoor space, so additional fresh air corresponds to a higher indoor ozone concentration and, thus, a higher I/O value. Conversely, higher CO_2 concentrations in an indoor space resulting from less air flow correspond with lower indoor ozone concentrations. This is due to both a lack of fresh air flow to supply ozone and an increase in the amount of time ozone has to react with surfaces and chemicals in the indoor environment.

The relationship between CO_2, ozone, and ventilation could have implications for future regulations of indoor air quality. Because the instrumentation for measuring CO_2 concentrations is generally less expensive, smaller, and portable, it could be beneficial to use CO_2 as an indicator of indoor ozone and other potentially harmful pollutants. Additionally, CO_2 measurement for demand-control ventilation is already a reality in some classrooms researched in this study, indicating the framework necessary to monitor CO_2 concentrations may already exist in some schools.

Chapter 5: Summary and Conclusions

A short summary and the conclusions of this study are presented in this chapter. Limitations of the study are outlined, and recommendations for further research are discussed.

5.1 SUMMARY

Through the course of a two-year field sampling campaign in thirty high school classrooms, relationships between carbon dioxide (CO_2), ventilation, and ozone were determined. Many classrooms were found to exceed the recommended maximum CO_2 concentration of 1100 ppm on average, although the second year of field work indicated a clear improvement with respect to average and peak CO_2 concentrations. Two specific types of classrooms, permanent and portable, were identified to have significantly different indoor environments when considering airflow as measured by CO_2 concentrations. On average, the permanent classrooms studied were found to receive less fresh air than recommended by ASRHAE Standard 62.1-2016 (ASHRAE, 2016), while portable classrooms were found to meet or exceed the recommendation prescribed by Standard 62.1-2016 due to infiltration of fresh air rather than an effort to operate and maintain HVAC systems.

Ozone concentrations were found to be heavily influenced by the operation of mechanical systems. Weekly ozone concentration profiles show close tracking between third-party ambient ozone measurements, rooftop measurements at the schools, and indoor ozone measurements in classrooms. A relationship between average CO_2 concentration and average indoor-to-outdoor (I/O) ozone concentration was found for both permanent and portable classrooms.

5.2 Conclusions

Ventilation is an important and influential component of the indoor space that has the ability to influence levels of pollutants such as CO_2 and ozone. Intentional or unintentional neglect of maintenance and operation of mechanical ventilation systems can result in poor environmental quality in classrooms. Measuring and monitoring the concentrations of common indoor pollutants can help alert school district officials to classrooms with poor indoor air quality. By investing more research and funds into optimizing ventilation to decrease levels of harmful pollutants, an improvement may be seen in student achievement.

5.3 Recommendations

More research is necessary to fully characterize the ventilation systems used in the schools researched in this study. Experiments incorporating more than one zone serviced by multi-zone Variable-Air-Volume (VAV) systems should be completed to fully understand the airflow characteristics. Additionally, student attendance data should be used to analyze results from the second year of field sampling further. If possible, results from student and teacher health surveys should be incorporated to determine how airflow characteristics in classrooms affect and possibly inhibit student sickness and attendance.

Appendices

APPENDIX A

Ventilation and Corresponding CO_2 Levels in High School Classrooms

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ABSTRACT

This paper reports findings about ventilation taken from a larger study of 30 high school classrooms in central Texas. Classrooms in portable buildings and permanent structures were sampled twice for four consecutive school days in the 2015-2016 school year. Carbon dioxide (CO_2) concentrations were measured in the supply airstream and the general room space. Average and peak CO_2 concentrations were used to estimate the risk of cold and flu transmission in schools during months of elevated sickness. It was found that average CO_2 concentrations during the occupied period in 81% of classrooms sampled in Fall 2015 and 72% of classrooms sampled in Spring 2016 exceeded the ASHRAE 62.1 recommendation for fresh air. When peak CO_2 concentrations during the same time periods were considered, 92% and 95% of classrooms in Fall 2015 and Spring 2016 exceeded this recommendation, respectively. Nighttime air exchange rates and occupied fresh air exchange rates were calculated for portable and permanent classrooms, and findings indicate that portable classrooms are dominated by occupant behavior, leaky building envelopes, and weather patterns.

1 INTRODUCTION

High school students spend approximately 1195 hours per year in classrooms where they are expected to learn and work effectively ("Public School Data File" 2008). In schools, where poor environmental quality can result in lost productivity, adequate ventilation is crucial to the success of students. Carbon dioxide (CO_2) has frequently been used to evaluate indoor ventilation because of its usefulness as a tracer gas and the ability to estimate human CO_2 production rates (Persily 1997). Poor ventilation may create uncomfortable thermal conditions, and CO_2 concentrations can indicate a buildup of indoor pollutants (Ramalho et al. 2015). Lack of ventilation has been associated with an increased risk of transmission of airborne diseases such as the cold and flu (Rudnick and Milton 2003). It has been suggested that lowering CO_2 concentrations by increasing ventilation is associated with a decrease in student absenteeism (Shendell et al. 2004; Gaihre et al. 2013). Recent research suggests students' academic performance can be improved by increasing ventilation (Haverinen-Shaughnessy et al. 2011; Haverinen-Shaughnessy et al. 2015; Mendell et al. 2015).

While studies of ventilation in schools have been conducted previously, many of these studies focused on elementary or middle schools (Corsi et al. 2002; Godwin and Batterman 2007; Gaihre et al. 2013; Mendell et al. 2015). There have been comparatively fewer studies done on high school classroom environments. Recent studies including high school classrooms have taken place in cold climates in the northern and western United States (Shendell et al. 2004; Grimsrud et al. 2006). More information about ventilation and the heating, ventilation, and air conditioning (HVAC) systems in high schools in a variety of climates is necessary.

This study characterizes the ventilation through the use of CO_2 concentrations in thirty high school classrooms in the hot, humid climate of central Texas. Specifically, this study examines average and peak CO_2 concentrations and the implications of these CO_2 levels for ventilation and student health. Air exchange rates are estimated using CO_2 concentrations and HVAC system data are reported when available.

2 METHODS

Data were gathered as a part of a three-year study of a variety of indoor environmental factors in high schools. This study, known as the Healthy High School PRIDE study, included seven high schools located in central Texas. Six schools (EP1, EP3, EP4, EP5, EP6, and EP7) are traditional public high schools in two school districts. These schools are large in population and area. In the 2015-2016 school year, each enrolled between 2400 and 3170 students in grades 9-12. These schools contain multiple wings, and several (EP1 and EP5) contain multiple permanent buildings. Four schools (EP3, EP4, EP6, and EP7) include portable classrooms, of which seven were used in this study. The schools range in age from five to thirty-five years old. One school (EP2) is a charter school for students in grades 6-12. This school is smaller and operates out of a rented building previously used for office space.

Four or five classrooms in each school were analyzed. These included general classrooms, science laboratories, computer laboratories, and portable classrooms. All general classrooms, science laboratories, and computer laboratories were located inside of larger, permanent buildings (collectively referred to as "permanent" classrooms throughout this text). Portable classrooms ("portables") are independent, nonpermanent structures generally located in parking lots or grass/soil fields adjacent to the school. The characteristics of permanent classrooms varied throughout each school. Most permanent classrooms were located on the exterior of the building (n=16), although some classrooms were located in the core of the building (n=7). All classrooms located on the exterior of the building contained windows, although none were openable. Interior rooms contained no windows to the outdoors. All portables had doors that immediately accessed outdoors and openable windows.

The chosen classrooms were analyzed twice throughout the 2015-2016 school year. The first sampling period, designated as "Fall 2015", took place during September, October, and November 2015. The second sampling period, designated as "Spring 2016", took place during February and March 2016. Sampling periods lasted four days (Monday afternoon through Friday afternoon) with the exception of EP2 in Spring 2016, which was only sampled for three full days. Table A1 outlines the number of classrooms chosen, types of classrooms, and dates of sampling for each school.

Table A1. Summary of the Classroom Types and Sampling Period

	Classrooms Sampled					Start Date*	
School Code	Total	Traditional	Science Lab	Computer Lab	Portable	Fall 2015	Spring 2016
EP1	4	2	2	-	-	09/28	03/07
EP2	4	2	2	-	-	09/21	03/21
EP3	4	1	1	-	2	11/02	02/22
EP4	4	1	1	-	2	10/19	02/08
EP5	4	1	2	1	-	10/12	02/15
EP6	5	1	1	1	2	10/26	02/01
EP7	5	2	1	1	1	10/05	02/29

*The sampling period was 4 days with one exception (EP2 was 3 days in the Spring 2016).

During each sampling period, two CO_2 sensors (Telaire 7001, Onset Corporation, Bourne, MA) connected to data loggers and temperature (T) sensors (HOBO U12, Onset Corporation, Bourne, MA) were deployed in the supply airstream and the general room area of the classroom. The CO_2 sensors have a measurement accuracy of $\pm$50 ppm or 5% of the measurement (whichever is greater). To measure T and CO_2 concentrations in the supply airstream, a set of sensors together with a data logger were placed inside ceiling diffusers or attached to wall diffuser grilles. To measure T and CO_2 concentrations in the room, another set of sensors and data logger were placed in a case in the classroom space. The location of the classroom sensors varied for each room due to teacher preference and proximity to an electrical outlet. Generally, the case containing the room air CO_2 sensor was placed on top of counters or cabinets.

The instruments recorded CO_2 concentrations every thirty seconds and were left in the classrooms for the duration of the sampling periods. Data from six classrooms (four in Fall 2015 and two in Spring 2016) were omitted from the results due to sensor failure. All classrooms were assumed to be well-mixed during the periods when the heating, ventilation, and air conditioning (HVAC) systems were operational. This assumption was further supported by flow rate measurements corresponding to air exchange rates (AER, h^{-1}) between 4 and 8 h^{-1} in representative classrooms included in the sample (Amai and Novoselac 2016).

During walkthroughs prior to and during sampling periods, classroom floor area and volume were recorded. Information about the HVAC systems was gathered by inspection of the systems and conversations with district employees. One school district containing five of the seven schools (EP3, EP4, EP5, EP6, and EP7) provided additional information about the operation of HVAC systems. Through collaboration with this district, the number of zones serviced by each HVAC system, methods of operation, and operational times of the systems were reported. The same district provided attendance data as reported by the classroom teachers during the weeks of the study. Because teachers in portables have autonomous control of the AC units servicing the classroom, runtime fractions were calculated. Runtime fractions were calculated by comparing changes in the temperature of the supply airstream to that of the room to determine when the system was heating or cooling (Thornburg et al. 2003).

Average CO_2 concentrations during the occupied period were calculated by averaging the recorded CO_2 measurements during the hours of school operation. Peak CO_2 concentrations were identified for the same period of time. To minimize the influence of a single extreme reading while calculating peak concentrations, the measurements were first averaged over periods of five minutes. The average CO_2 concentration can be roughly related to the risk of infectious disease transmission using the rebreathed fraction (RF) as a screening model (Rudnick and Milton 2003). The RF is a function of indoor CO_2 concentration (c), outdoor CO_2 concentration (c_o), and exhaled CO_2 concentration (c_a). The RF provides a measure of the fraction of air in an indoor space that has been previously exhaled by another occupant and is given by the following equation:

$$RF = \frac{c - c_o}{c_a} \tag{1}$$

In all cases, the outdoor CO_2 concentration was assumed to be 400 ppm based on measurements taken throughout the year of study. The value for c_a was assumed to be 38,000 ppm for all occupants, including both students and teachers (*ASTM* 2012; *ASHRAE* 2013).

Nighttime air exchange rates of fresh air (designated as "night AER_f,") values were calculated using the CO_2 decay method for each classroom in the five schools (EP3, EP4, EP5, EP6, and EP7) for which the most detailed HVAC system information was known (*ASTM* 2013). The air exchange rate of fresh air during the school day was evaluated during the occupied hours of the same five schools (designated as "occupied AER_f"). A steady-state analysis was performed using room air CO_2 concentrations to compare ventilation in portable and permanent classrooms. The CO_2 concentration in the room was considered at steady-state if the coefficient of variation was less than 10% over the time period analyzed. A uniform CO_2 generation rate of 0.31 L/min was assumed when calculating occupied AER_f values (Persily 1997). The generation rate was assumed uniform for adolescents and adults due to the similarities in body size and a lack of knowledge about the exact size and age of students in classrooms studied.

3 RESULTS

Variable Air Volume (VAV) systems with the ability to reheat were the most prominent system used in permanent buildings. Though VAV systems were most common, the number of zones connected varied throughout each school. One school employed only split-systems in permanent buildings and supplied conditioned air to each classroom individually. In all schools, teachers were generally able to control temperature, although some classrooms did not have a thermostat and were instead dependent on the control exercised in adjacent classrooms. The type of heating, ventilation, and air conditioning (HVAC) system used by each portable classroom, regardless of the school, was a wall air conditioning (AC) unit. Each portable classroom was serviced by its own wall AC unit that could be controlled by the teacher. Table A2 contains the types of HVAC systems connected to the classrooms, the number of zones serviced by each HVAC system, and the runtime fractions for portable classrooms.

Table A2. Classroom HVAC Characteristics

School Code	Classroom Type	Type of HVAC System	Number of Zones	Runtime Fraction (Fall)	Runtime Fraction (Spring)
EP1	Science Lab	Single Zone On/Off	1	-	-
	Engineering Lab	Single Zone On/Off	1	-	-
	Traditional	Multizone VAV	N/A	-	-
	Traditional	Multizone VAV	N/A	-	-
EP2	Science Lab	N/A	N/A	-	-
	Science Lab	N/A	N/A	-	-
	Traditional	N/A	N/A	-	-
	Traditional	N/A	N/A	-	-
EP3	Traditional	Multizone VAV with Reheat	35	-	-
	Science Lab	Multizone VAV with Reheat	16	-	-
	Portable	Wall AC Unit	1	0.39	0.28
	Portable	Wall AC Unit	1	0.3	0.26
EP4	Science Lab	Multizone VAV with Reheat	20	-	-
	Traditional	Multizone VAV with Reheat	20	-	-
	Portable	Wall AC Unit	1	0.53	0.48
	Portable	Wall AC Unit	1	0.48	N/A
EP5	Traditional	Multizone VAV with Reheat	6	-	-
	Science Lab	Multizone VAV with Reheat	31	-	-
	Science Lab	Fan-Coil	1	-	-
	Computer Lab	Multizone VAV with Reheat	10	-	-
EP6	Traditional	Split System	1	-	-
	Science Lab	Split System	1	-	-
	Computer Lab	Split System	1	-	-
	Portable	Wall AC Unit	1	0.53	0.62
	Portable	Wall AC Unit	1	0.74	0.04
EP7	Traditional	Multizone VAV with Reheat	8	-	-
	Science Lab	Multizone VAV with Reheat	12	-	-
	Computer Lab	Multizone VAV with Reheat	4	-	-
	Traditional	Penthouse with Chilled Water	N/A	-	-
	Portable	Wall AC Unit	1	0.42	0.28

The four-day average CO_2 concentrations measured during occupied periods in the classrooms sampled during the fall (n=26) and the spring (n=28) sampling periods ranged from 500 to 2000 ppm (Figure A1(a)). The recommendation for fresh air provided by the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) in Standard 62.1 is a function of occupancy and floor area (*ASHRAE* 2016). For typical classroom size and student occupancy, this standard results in a steady-state CO_2 concentration of 700 ppm above the background level. For an atmospheric CO_2 concentration of 400 ppm, the maximum recommended CO_2 concentration in each classroom is 1100 ppm. However, the average CO_2 concentration measured in 81% of classrooms sampled in Fall 2015 and 72% of classrooms sampled in Spring 2016 exceeded this limit.

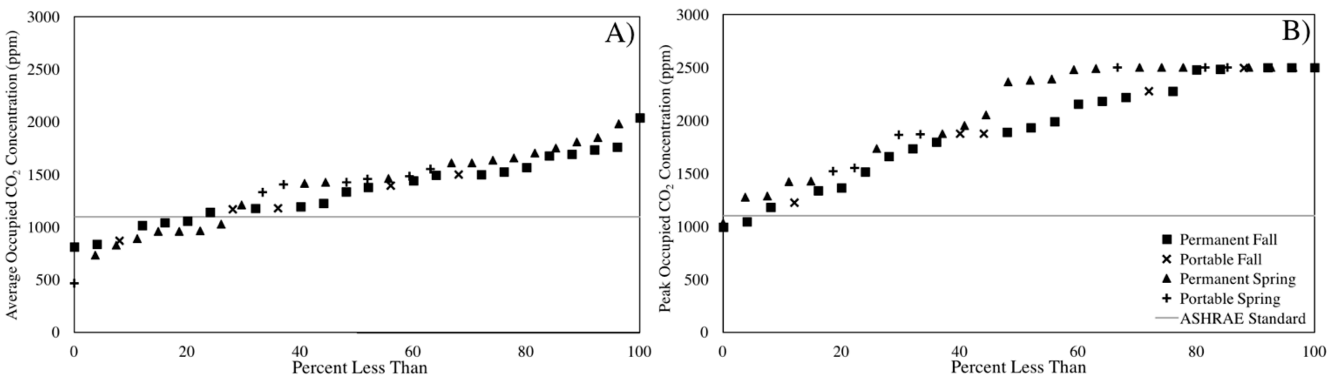

Figure A1: Average (a) and peak (b) occupied day CO_2 concentrations in classrooms sampled in the Fall 2015 (n=26) and Spring 2016 (n=28) sampling periods compared to the recommended standard (*ASHRAE* 2016).

Peak CO_2 concentrations measured during occupied periods in the fall and spring sampling periods ranged from 1000 to 2500 ppm (Figure A1(b)). It should be acknowledged that the sensors and data loggers used in this study were only able to record CO_2 concentrations up to 2500 ppm. Compared to the recommended limit of 1100 ppm provided by ASHRAE Standard 62.1, 92% of classrooms sampled in Fall 2015 and 97% of classrooms sampled in Spring 2016 exceeded this reference. When the upper limit is considered, it is likely that many classrooms with peak CO_2 concentrations recorded as 2500 ppm actually exceeded this value for extended periods of time.

Rebreathed fractions (RF) for classrooms in the Fall 2015 and Spring 2016 sampling periods were calculated using the average occupied CO_2 concentrations (Figure A2). These values correspond directly to the average CO_2 concentrations and provide a measure of the amount of air previously exhaled by occupants in a classroom. Increasing RF indicates an increased chance for the spread of airborne illnesses during the cold and flu season.

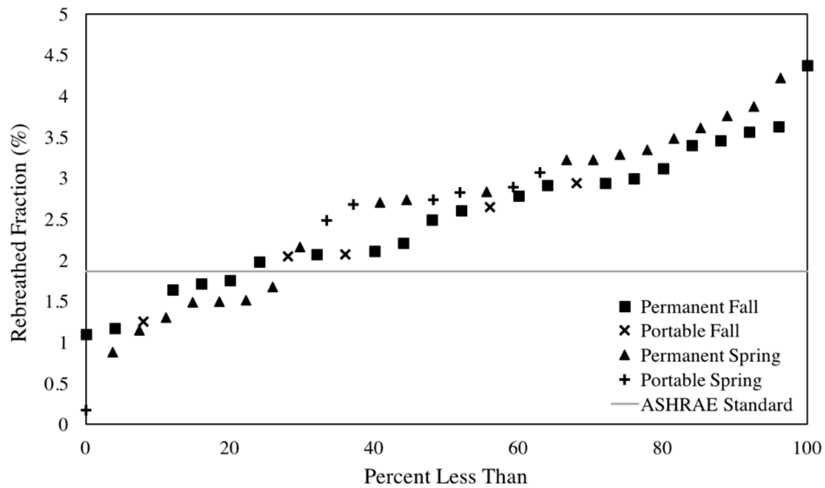

Figure A2: Average rebreathed fractions (%) in classrooms sampled in the Fall 2015 (n=26) and Spring 2016 (n=28) sampling periods compared to the resulting rebreathed fraction when using the recommended standard (*ASHRAE* 2016)

Average night AER_f values (h^{-1}) were calculated for EP3, EP4, EP5, EP6, and EP7 (Figure A3(a)). These values represent the ventilation rate when the HVAC systems are switched off. Values for average night AER_f for permanent classrooms and portable classrooms in both sampling periods ranged from 0.0 to 1.4 h^{-1} with average values of 0.2 to 0.8 h^{-1}. In general, the variation of night AER_f values was greater for portable classrooms than permanent classrooms in both sampling periods.

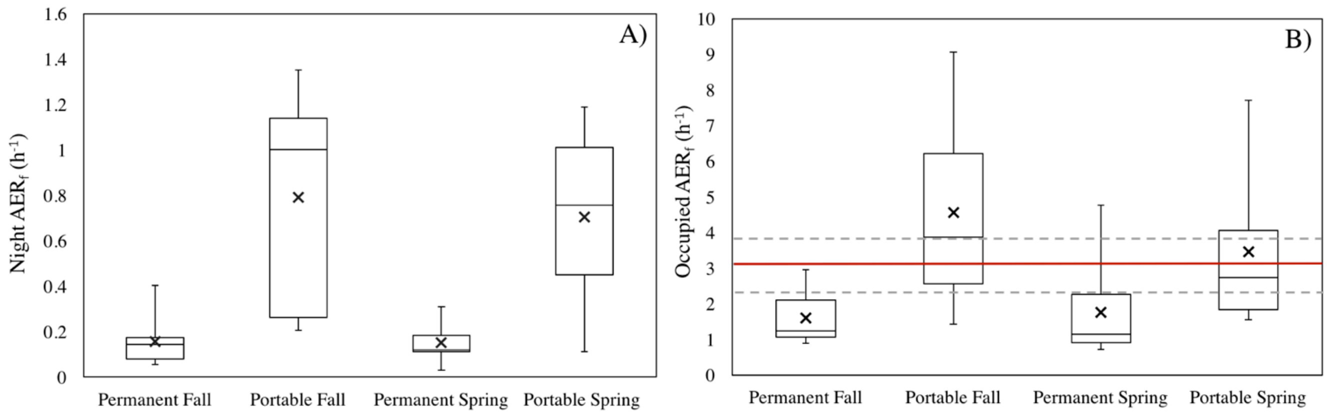

Figure A3: Box plot of average AER_f (h^{-1}) during the overnight periods (a) and occupied periods (b) in permanent classrooms and portable classrooms during the Fall 2015 and Spring 2016 sampling periods. Overall averages are indicated by the single point in each box. Night AER_f box plots were constructed by averaging nightly decay measurements for permanent (n=14 for fall, n=13 for spring) and portable (n=5 for fall, n=4 for spring) classrooms. Occupied AER_f box plots were constructed by averaging daily steady-state analysis results for permanent (n=13 for fall, n=12 for spring) and portable (n=6 for fall and spring) classrooms. The average minimum acceptable ventilation is indicated by the solid line. One positive and negative standard deviation is indicated by the dashed lines.

Average occupied AER_f values (h^{-1}) were calculated for EP3, EP4, EP5, EP6, and EP7 (Figure A3(b)). Several (2-5) AER_f values were calculated per classroom. The number of values calculated per room depended on the number of instances in which CO_2 concentrations remained at steady-state for at least an hour. The overall AER_f value for each classroom was calculated by averaging the results of each steady-state analysis. The range of average occupied AER_f values in permanent and portable classrooms ranged from 0.1 to 9.1 h^{-1} with averages ranging from 1.6 to 4.6 h^{-1}.

For each occupied AER_f value calculated, the minimum amount of fresh air required was calculated as a function of floor area and the number of occupants in each classroom (*ASHRAE* 2016). The average minimum requirement of fresh air is shown, along with one positive and negative standard deviation, in Figure A3(b). Analyses were not performed on the total AER due to uncertain data in the CO_2 sensors measuring supply air. Like the night AER_f values, the occupied AER_f values during occupied period in portable classrooms was highly variable.

4 DISCUSSION

This study provides a "snapshot" of CO_2 levels in classrooms for two weeks out of the school year. This snapshot presents evidence that many classrooms have average CO_2 concentrations above the recommended level of 1100 ppm. Average CO_2 concentrations determined in this study are within the same range as those reported by Shendell et al. in primary and secondary schools in Washington and Idaho (Shendell et al. 2004). When peak CO_2 concentrations are considered, most classrooms in the study exceeded the recommended level for some period of time. When peak CO_2 concentrations are compared to the results of Shendell et al., they fall within the lower range of the reported data (Shendell et al. 2004). This is likely due to the upper limit of measurement of 2500 ppm for the instruments used in this study. Though the instruments used had a maximum limit of 2500 ppm, concentration profiles suggest that peak CO_2 levels often exceeded 2500 ppm in classrooms with the highest concentrations.

In the context of cold and flu season, high CO_2 concentrations indicate a greater likelihood for disease transmission. Lowering rebreathed fractions through ventilation can reduce the potential for the spread of airborne illnesses. Lost productivity from teacher and student absences can possibly be reduced for the schools in this study by simply increasing the ventilation during cold and flu season.

Most schools included in the study contained had similar heating, ventilation, and air conditioning (HVAC) systems in place to service all classrooms in permanent structures. Four out of the five schools further analyzed used identical systems, Multizone VAV with Reheat, with the only difference being the number of zones connected to each system. Though these schools had identical systems operated by the same employees, the classrooms corresponding to these schools represented a spectrum of concentrations of CO_2 ranging from 1050 ppm to 2040 ppm. More than the type of system used to service each classroom, it is likely the number of zones, the amount of recirculated air, and the population density that influence the level of CO_2 and other pollutants in classrooms.

The reported night AER_f values (h^{-1}) indicate overnight ventilation in portable classrooms was more variable than in permanent classrooms. School district utility managers confirmed that HVAC systems are shut down completely overnight and restarted in the early morning before students arrive at school. Because of this, the nighttime AER_f values represent naturally occurring airflow. Generally, these findings indicate that permanent buildings have much tighter envelopes than portable structures. Each portable classroom is unique, and the characteristics of its structure depend on its age, construction, usage, and location. While some portable classrooms may have tight building envelopes like those of permanent structures, some portable classrooms have much "leakier" envelopes. In all classrooms studied, overnight ventilation was sufficient to lower CO_2 concentrations to background levels before the start of the following school day. However, in all schools studied, the janitorial staff cleans in the hours immediately after school, when HVAC systems are shut off and little natural ventilation occurs. Cleaning under conditions of minimal ventilation can increase exposure to harmful chemicals in cleaning products.

Analysis of the occupied AER_f values indicates that portable classroom ventilation during the school day was more variable than permanent classrooms. The large range of AER_f values in portable classrooms indicates the ventilation is dominated by external factors such as opening doors and windows, teacher preference for the classroom temperature, and weather. Permanent classrooms have less variability due to tighter building envelopes and less control for teachers when regulating temperature.

When compared with the average fresh air recommendation of 3.1 h^{-1}, most classrooms studied did not receive the amount of fresh air suggested by the 2016 edition of ASHRAE Standard 62.1. The average occupied AER_f values for permanent classrooms in both sampling periods were well below 3.1 h^{-1}, indicating that most were under-ventilated with respect to fresh air. In general, portable classrooms received more fresh air, although this may be due to the leakiness of the building envelope and/or the ability of teachers to easily use natural ventilation. The large leakage of portable classrooms encouraged utility managers to permanently close fresh air dampers for the unit AC systems installed in these buildings by taping or nailing them shut. This was done because the cooling load was often exceeded on hot days when the systems were allowed to take in fresh air. Due to this, most portable classrooms sampled (6 out of 7) relied on infiltration only for bringing outdoor air to the classroom.

5 CONCLUSION

In this study, it was found that many classrooms exceeded the recommended maximum CO_2 concentration of 1100 ppm during the occupied time period. In addition to creating distracting physical conditions such as thermal discomfort or the presence of odors, elevated levels of CO_2 indicate insufficient ventilation.

Portable classroom ventilation was found to be much more variable than the ventilation in permanent buildings both overnight, when the HVAC systems are shut off, and during the occupied school day. The variability in portable classroom ventilation suggests these environments are susceptible greater ventilation because of leaky building envelopes, teacher preference, and weather patterns. While portable classrooms, on average, were found to have better ventilation than traditional classrooms, it is important to acknowledge that each portable classroom is unique and together they represent a spectrum of environments for students and teachers. Further research is necessary to fully characterize the influences on ventilation in portable and traditional classrooms.

ACKNOWLEDGEMENTS

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APPENDIX B

Ozone Concentrations in Permanent and Portable High School Classrooms

Lesnick, L., Novoselac, A., Crain, N., and Corsi, R.L.

Introduction

Schools have a unique place in the fabric of America. Primary and secondary education ranks as the largest public enterprise in the United States, and educational service is the second leading "industry" (Godwin and Batterman, 2007; Tak et al., 2011). Public K-12 schools serve as a place to work or learn for more than 15% of the total population of the United States each year (Common Core of Data, 2016). Additionally, children spend 1.6 total years *inside* school buildings by the time they graduate from high school (Juster et al., 2004).

Despite their importance, schools face major challenges that can affect the health and performance of both students and teachers, and are particularly vulnerable to environmental deficiencies because of inadequate budgets for operation and maintenance (Mendell and Heath, 2005). Because of the relatively high occupant density of school buildings and their unique mixture of pollutant sources, solutions to indoor air quality problems in schools are often complex (Jones et al., 2010). Further, research is lacking to fully understand these problems, thus limiting opportunities for low-cost and effective solutions.

There is growing evidence that poor indoor air quality leads to increases in student illnesses and absenteeism, and decreases in academic performance (Shendell et al., 2004; Jones et al., 2007; Jones, et al., 2010; Almeida et al., 2011; Lin et al., 2012; Haverinen-Shaughnessy et al., 2015). Teachers are also affected, with higher rates of work-related upper-respiratory problems compared to the rest of the working population (Tak et al., 2011). Combined, these effects come with considerable costs related to children's health, inferior learning conditions, absenteeism, reduced funding to school districts, crisis remediation of school facilities, and negative stigmatization of affected schools (Alsmo and Holmberg, 2007; Jones et al., 2007; Lin et al., 2012).

One pollutant that has received little attention inside of school classrooms is ozone. Ozone exposure has been shown to damage the lung tissue at a cellular level, with associated increases in respiratory related illnesses (Mudway and Kelley, 2004; Adams, 2006; USEPA, 2006a; Brown et al., 2008). The risk for a particular respiratory illness, asthma, has been shown to increase with increasing ambient ozone concentrations (McDonnell et al., 1999; Glad et al., 2012).

Detrimental health effects of ozone occur in children. Increased childhood ozone exposure has been linked to decreased airway function (Tager et al., 2005). Increased asthma diagnoses in adolescents, particularly those who spend extended time outdoors, have been associated with ozone exposure (McConnell et al., 2002). Increased visits of children to the emergency room were linked to a 10 ppb increase in ambient ozone (Yang et al., 2003).

Though past research related to population exposures to ozone has focused on outdoor air, the penetration of outdoor ozone into buildings and subsequent exposure of building occupants can be significant (Weschler et al., 1989; Chen et al., 2012). In school environments there can also be important indoor sources of ozone, including in-use photocopy machines, laser printers, air cleaners, and other electronic equipment shown to generate ozone (Leovic et al., 1996; Britigan et al., 2006; Phillips and Jakober, 2006; Destaillats et al., 2008; Morrison et al., 2014; Zhang and Jenkins, 2016). Exposure to high levels of ozone (>0.13 ppm) has been associated with an increase in respiratory-illnesses and absences from school in Mexico City (Romieu et al., 1992). Additionally, ambient ozone concentrations have been associated with increased student absenteeism in both the United States and South Korea (Chen et al., 2000; Gilliland et al., 2001; Park et al., 2002a; Hubbell et al., 2005).

Exposure to ozone indoors is accompanied by additional exposure to ozone-initiated reaction products that are formed when ozone reacts with VOCs emitted from or associated with the surfaces of carpet, cleaning supplies, air fresheners, and more (Weschler 2004; Weschler, 2006). These gaseous and particulate reaction products may be irritating or toxic (Baldwin et al., 1999; O'Connor, 2005; Bernard, et al., 2005; Gilmour, et al., 2006; Eggleston, 2009). Occupants of the indoor environment are themselves a source of reactive material for ozone, with large sources of an ozone-reacting chemical, squalene, found in human skin oils (Weschler 2015).

Several recent studies have illuminated the additional exposure students may receive to ozone-initiated reaction products. Elevated levels of ultrafine particles thought to be from ozone-initiated reactions were found in elementary schools during periods of art class or when the space was cleaned (Morawska et al., 2009). Ozone has also been shown to react with scenting agents used in children's markers to form ultrafine particles, indicating a potentially unseen consequence of arts and crafts in schools (Fung et al., 2014).

The relationship between indoor and ambient ozone concentrations is important when considering the exposure and related health implications for school occupants. Because mechanical ventilation is used in most buildings to supply fresh air to indoor spaces, the relationship between heating, ventilating, and air conditioning (HVAC) systems and indoor ozone concentrations is important (Lee et al., 1999). Specific guidelines given by the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) in Standard 62.1 recommend minimum flowrates of fresh air necessary for indoor spaces, including educational facilities (ASHRAE, 2016). While overventilation of an indoor space is generally preferred to dilute indoor pollutants and odors, increasing the supply of fresh air can increase exposure to outdoor pollutants such as ozone (Yu et al., 2014). More research is necessary to determine the relationship between ambient ozone concentrations, indoor ozone concentrations, and mechanical ventilation systems, particularly in the occupant-dense environment of a school.

Ambient and indoor ozone concentrations recorded in thirty high school classrooms in central Texas are reported in this paper. Specifically, weekly profiles of ozone concentrations and the indoor-to-outdoor ratio of ozone concentration during student-occupied periods are reported. Carbon dioxide (CO_2) concentrations and air exchange rates (AERs) are compared to indoor ozone concentrations to better understand the relationship between ventilation and indoor ozone.

Methods

The information presented in this paper was collected as a part of a larger research project known as the Healthy High School PRIDE (**P**artnership in **R**esearch on **I**n**D**oor **E**nvironments) study. This four-year study is ongoing at seven diverse high schools in central Texas and included four semesters of field research completed during the 2015-2016 and 2016-2017 school years. A subset of data from five of the seven schools for which ample meta data were available are presented in this paper.

The five high schools analyzed (denoted as EP3, EP4, EP5, EP6, and EP7) are part of the same school district. Each school building contains multiple large wings, and one school (EP5) has multiple permanent buildings. The high schools enrolled between 2,600 and 3,200 students in grades 9-12 during the periods of field research. The schools ranged in age from between five and thirty-five years old.

Meta data were collected for each high school. For example, prior to and during the study, walkthroughs were conducted in each classroom at each school to record the floor area, volume, and any interesting and relevant features, e.g., clutter or presence of a scented air freshener. Through extended collaboration with school district facilities staff, information about the types and operations of the heating, ventilating, and air conditioning (HVAC) systems used in the five schools was obtained. A tabular summary of the types of mechanical systems, number of zones connected to each air handling unit, and information about HVAC operation is provided as supplementary information (see Table S1). Additionally, each school provided daily attendance data for the classrooms studied during the first two semesters (2015-2016 school year).

Four sampling events were conducted for the Healthy High School PRIDE study beginning in the fall of 2015. In the 2015-2016 school year, the first phase of sampling took place in September, October, and November ("Fall 2015"), while the second phase of sampling took place in February and March ("Spring 2016"). In the 2016-2017 school year, the third phase of sampling took place in October and November ("Fall 2016"), while the fourth phase of sampling occurred in January, February, and March ("Spring 2017"). For all sampling events, instruments were deployed at the school sites after class on Monday afternoons and were left in the field to monitor continuously until the end of the school week on Friday afternoons. All field sampling periods lasted for four full days. UV-absorbance ozone analyzers (2B Technologies, Boulder, CO) were used to measure and record ozone concentrations. The ozone analyzers have a measurement accuracy of ± 1.5 ppb or 2% of the measurement (whichever is greater). During most field sampling events, an ozone analyzer was placed on the roof of the school to monitor ambient ozone concentrations. The ozone analyzer on the roof was placed in a large, weather-resistant box, and a sample tube was used to pull ambient air through the analyzer. The ozone concentrations recorded on the roof were compared with ambient ozone concentrations recorded by a nearby Continuous Air Monitoring Station (CAMS) operated by the Texas Commission on Environmental Quality (TCEQ). Table B1 provides information about the start dates of each sampling period, the distance between each school site and the CAMS, and whether or not ambient roof measurements were taken.

Table B1: Distance between each school site and the Continuous Air Monitoring Station (CAMS), start date of the sampling events at each school site, and information about ambient ozone measurements at each school site.

	Distance (km) and direction of school from CAMS	Fall 2015		Spring 2016		Fall 2016		Spring 2017	
		Start Date	Roof Data	Start Date	Roof Data	Start Date	Roof Data	Start Date	Roof Data
EP3	19.3 NE	11/02	P	02/22	Y	10/24	Y	01/30	Y
EP4	11.3 NE	10/19	Y	02/08	Y	10/03	Y	02/13	Y
EP5	17.7 NE	10/12	Y	02/15	Y	11/14	Y	02/06	Y
EP6	22.5 NE	10/26	Y	02/21	Y	11/07	Y	03/20	Y
EP7	11.3 NW	10/05	Y	02/09	Y	10/10	N	02/20	Y

Note: Y indicates that rooftop measurements were taken, N indicates they were not, and P indicates that partial data are available.

Ozone analyzers were placed in two or three classroom at each school during a sampling phase. During one field sampling event in Fall 2015, ozone analyzers were placed in four classrooms. Ozone analyzers were placed both in traditional classrooms located in permanent structures ("permanent classrooms") and classrooms located in portable structures ("portables"). The ozone analyzers in classrooms were placed in a muffle box to minimize class disruption, and a sample tube was used to pull classroom air through the device. Muffle boxes were generally placed atop counters or cabinets to minimize student interference.

Some classrooms were monitored multiple times over the four sampling phases, while other classrooms were monitored only once. Generally, the same classrooms were studied in the Fall and Spring sampling phases of each year, with a few adjustments made to compensate for available equipment. During the first year of study, the overall amount of rooms monitored (n=18) was composed of both permanent (n=12) and portable (n=6) classrooms. Some new classrooms were chosen for study in the second year (n=12), of which most were permanent classrooms (n=11) and one was a portable. During the second year of field sampling, some classrooms previously investigated were chosen to remain in the study (n=7). Table B2 summarizes the number of permanent and portable classrooms studied at each school.

Table B2: Summary of the number of classrooms located in permanent structures ("permanent") and portable structures ("portable") studied in each sampling period at each school site.

	Fall 2015			**Spring 2016**			**Fall 2016**			**Spring 2017**		
	Total	Permanent	Portable	Total	Permanent	Portable	Total	Permanent	Portable	Total	Permanent	Portable
EP3	3	1	2	3	1	2	3	2	1	3	1	2
EP4	3	2	1	1	1	0	3	2	1	3	1	2
EP5	4	4	0	1	1	0	3	3	0	3	3	0
EP6	3	2	1	0	0	0	3	2	1	3	2	1
EP7	3	2	1	3	2	1	3	2	1	3	2	1
Total	16	11	5	8	5	3	15	11	4	15	9	6

All permanent classrooms studied (n=23) had inoperable (unable to open) windows, as well as doors that did not immediately access the outdoor environment. The portable classrooms studied (n=7) had operable windows and doors that immediately accessed the outdoor environment. In general, the portable classrooms were much less spacious than permanent classrooms due to lower ceilings and reduced floor area. Attendance data provided by the school district for the first year of field sampling indicate that there is no difference in average class size between permanent and portable classrooms. Because of this, portable classrooms were found to be more densely populated than permanent classrooms. The average population density was 0.12 and 0.08 occupants per cubic meter for portable and permanent classrooms, respectively.

Carbon dioxide (CO_2) concentrations were also monitored in each classroom. One CO_2 sensor (Telaire 7001, Onset Corporation, Bourne, MA) was connected to a data logger (HOBO U12, Onset Corporation, Bourne MA) and placed inside a muffle box. The CO_2 sensors have a measurement accuracy of ± 50 ppm or 5% of the measurement (whichever is greater). The data logger was only able to record CO_2 concentrations up to 2500 ppm. Muffle boxes containing the CO_2 sensors were generally placed in the same locations as the muffle boxes containing ozone analyzers. CO_2 concentrations were recorded every thirty seconds throughout the four-day sampling period.

Average CO_2 concentrations during the occupied time periods were calculated from thirty-second incremental data. Peak CO_2 concentrations were calculated using five-minute averages to minimize the effect of a single extreme reading. Using steady-state and dynamic mass balance analyses and the corresponding volume and occupancy of each classroom, fresh air exchange rates (AER_f, h^{-1}) were calculated (Lesnick et al., 2017). Classrooms were considered to be at steady-state if the coefficient of variation was less than 10% over the time period in which the analysis was conducted. Because information influencing metabolic rate such as student age, weight, and activity levels were unknown, a uniform generation rate of 0.31 L CO_2 / min per occupant was assumed when analyzing AER_f values (Persily, 1997).

Results

Weekly ozone concentration profiles indicate close tracking between a nearby Continuous Air Monitoring Station (CAMS) and the ozone analyzer placed on the roof of the school (Figure B1). This was true for all schools in the study.

Significant differences in indoor ozone concentration and concentration dynamics were observed between classrooms. While ozone concentrations below 15 ppb were typically recorded in permanent classrooms, several permanent classrooms reached higher ozone concentrations during peak hours for outdoor ozone concentration. Reasons for the differences in ozone concentrations in permanent classrooms may include proximity to an external door or differences in the operation of the heating, ventilating, and air conditioning (HVAC) system servicing the classrooms. The operation of HVAC systems influences indoor ozone concentrations by regulating the amount of fresh air supplied to a classroom. Because the largest source of ozone in the indoor environment is ambient air, HVAC systems that bring in more fresh air and recirculate less from other classrooms cause higher levels of ozone in classrooms connected to these systems.

Further, lower outdoor air exchange rates provide for greater time for ozone reactions, and thus concentrations reductions, in the indoor environment.

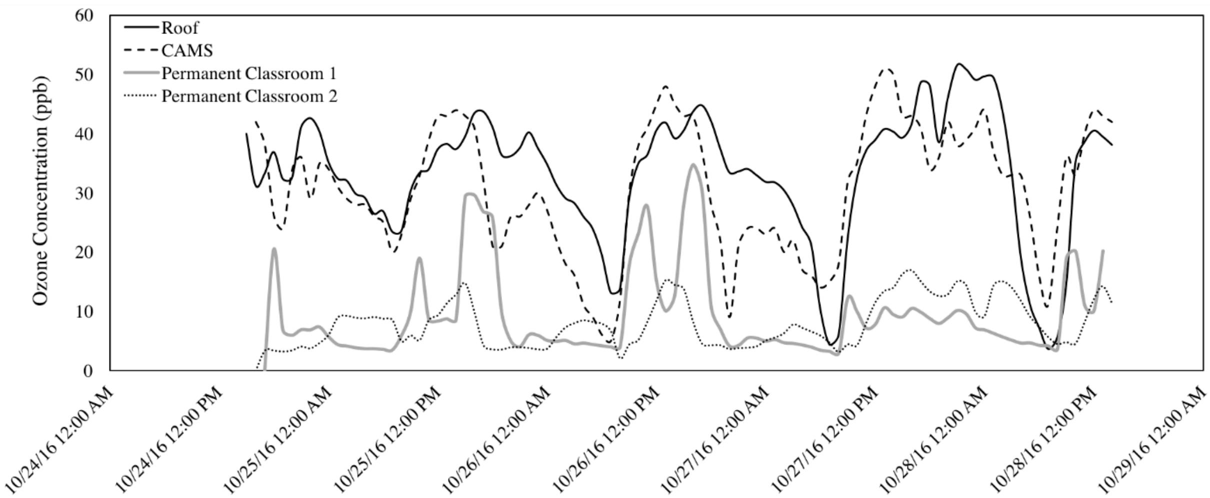

Figure B1: Sample weekly ozone concentration profile for one school studied in Fall 2016. Measurements taken by the Texas Commission on Environmental Quality (TCEQ) at a Continuous Air Monitoring Station (CAMS) are compared to measurements taken on the roof of the school. Two permanent classrooms serviced by different air handling units are shown.

In most schools, the influence of mechanical ventilation on the indoor ozone concentrations was apparent from examination of weekly concentration profiles (Figure B2). While measurements taken by nearby CAMS and on the rooftop of each school increase and decrease synchronously, indoor ozone concentrations often decrease abruptly at the end of the school day, peaking prior to the ambient ozone peak. This abrupt truncation of the indoor ozone concentration profile corresponds with the time when mechanical ventilation systems are programmed to shut down each day.

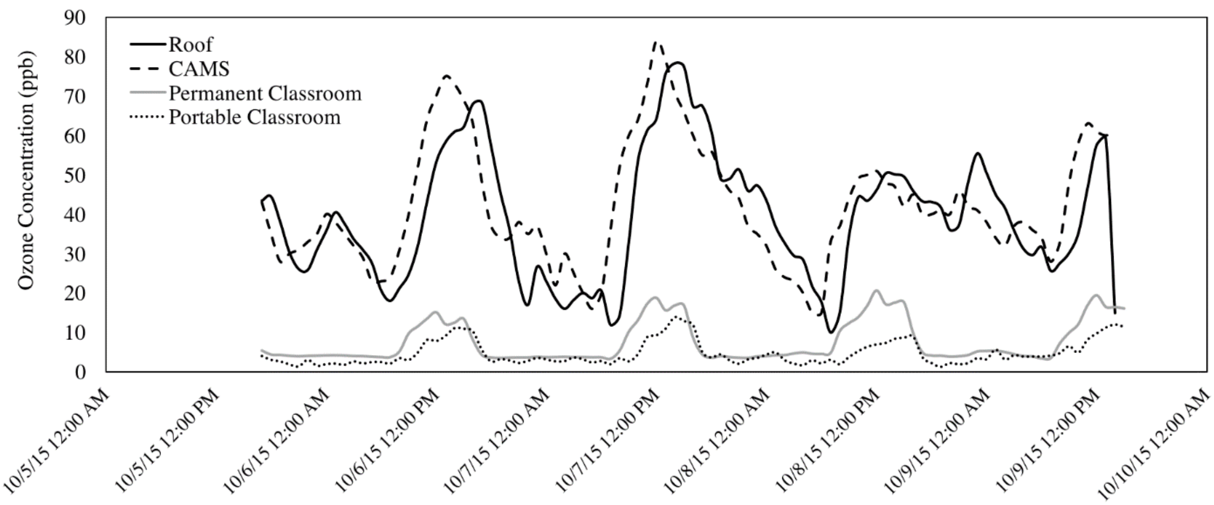

Figure B2: Sample weekly ozone concentration profile for one school studied in Fall 2015. Measurements taken by the Texas Commission on Environmental Quality (TCEQ) at a Continuous Air Monitoring Station (CAMS) are compared to measurements taken on the roof of the school. One portable classroom and one permanent classroom are included for comparison.

In general, portable classrooms displayed different indoor ozone concentration profiles than permanent classrooms, as illustrated in Figure B3. The indoor ozone concentration in portable classrooms was generally more variable and typically reached higher levels than in permanent classrooms. This may be due to the leaky building envelopes of portable structures, the ability of occupants to have greater control over ventilation, the type of HVAC systems used in portable classrooms, and a generally higher outdoor air exchange range for portable classrooms. Peak ozone concentrations in the portable classroom shown in Figure B3 reached relatively high values compared to permanent classrooms in our study. For the two classrooms shown in Figure B3, the average four-day indoor-to-outdoor (I/O) ozone concentration ratios were 0.25 and 0.10 for the portable and permanent classroom, respectively.

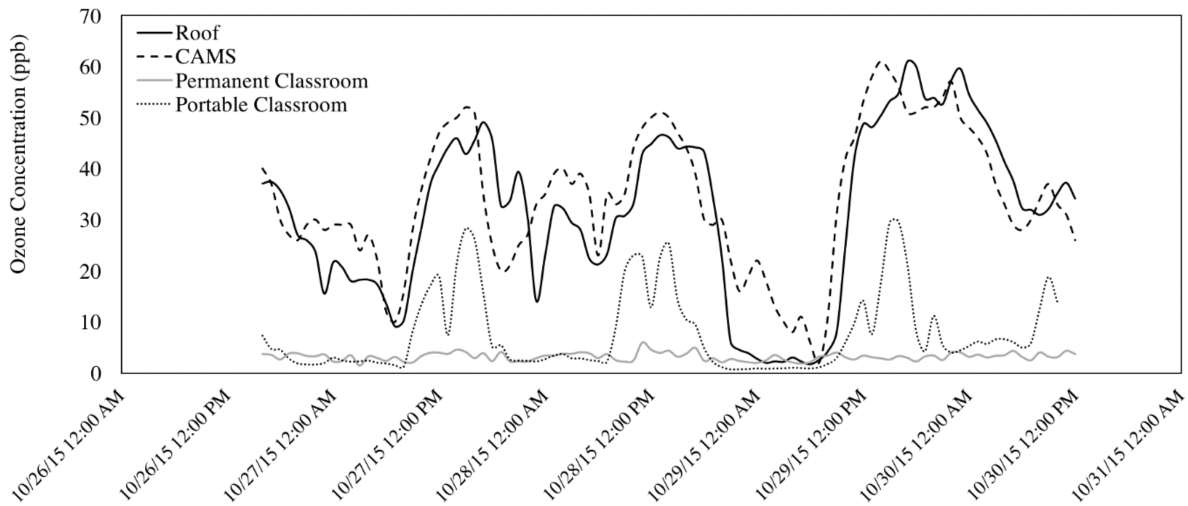

Figure B3: Sample weekly ozone concentration profile for one school studied in fall 2015. Measurements taken by the Texas Commission on Environmental Quality (TCEQ) at a Continuous Air Monitoring Station (CAMS) are compared to measurements taken on the roof of the school. One permanent classroom and one portable classroom at the school site are included and compared.

Average indoor-to-outdoor ozone concentration ratios (I/O) over the entire occupied period were calculated for all classrooms in each field sampling season (Figure B4). Average I/O in each classroom ranged from 0.04 to 0.69 across all sample events. The range of average occupied I/O was relatively similar throughout all phases of the field campaign. Overall average I/O for each sampling phase ranged from 0.16 in Fall 2015 to 0.25 in Fall 2016.

Portable classrooms (denoted by open data points in Figure B4) were always in the top 25th percentile of I/O. However, the portable I/O still displayed a spectrum of values over each sampling period.

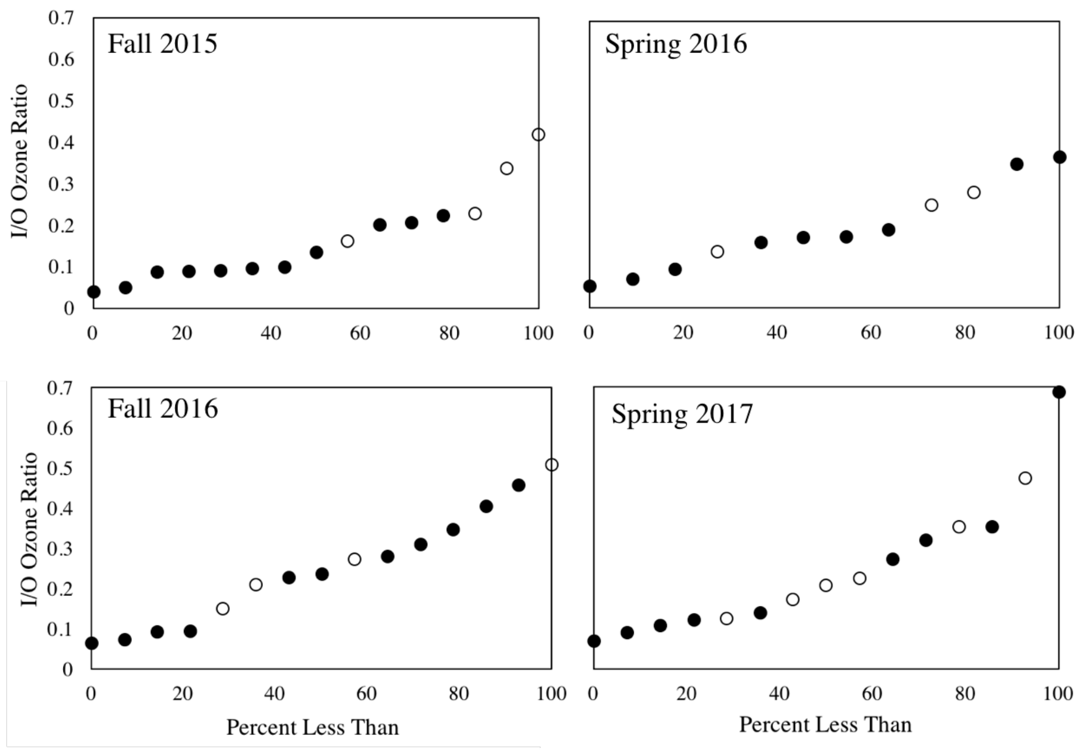

Figure B4: Average indoor-to-outdoor (I/O) ozone concentration ratios for all classrooms studied during each of the sampling periods. Permanent classrooms are represented by closed data points, and portable classrooms are represented by open data points.

The four-day average carbon dioxide (CO_2) concentrations in classrooms were compared to the four-day average I/O ozone concentration ratios during the occupied day, and a clear trend between the two metrics was observed (Figure B5). Examination of the interaction between I/O greater than 0.1 and average CO_2 concentrations in permanent classrooms indicates a linear relationship with a slope of -0.0004 and an intercept of 0.68 (Figure B5A). Examination of the interaction between I/O greater than 0.1 and average CO_2 concentrations in portable classrooms indicates a linear relationship with a slope of -0.0002 and an intercept of 0.51 (Figure B5B). Classrooms in which the I/O was less than 0.1 were excluded from the linear regression analysis due to both uncertainty in measurement and the clear convergence of these data points with the abscissa.

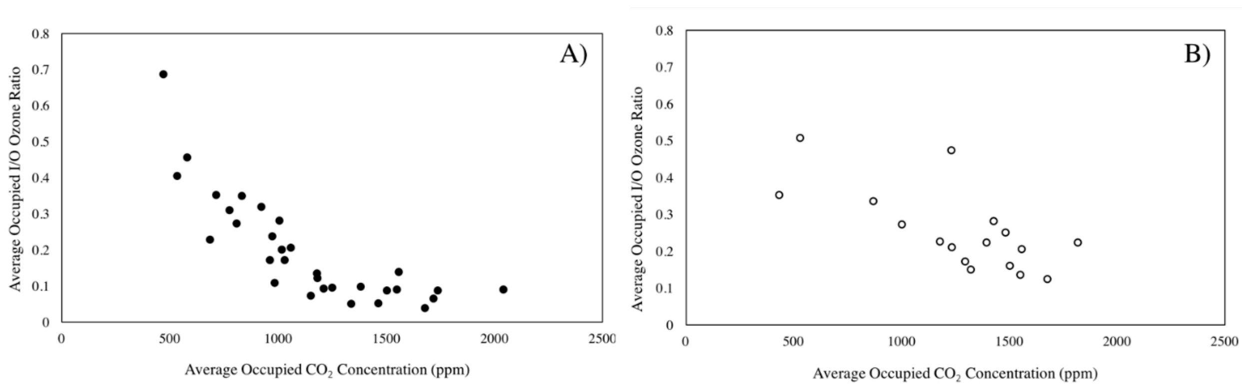

Figure B5: Scatter plot showing the relationship between the average occupied indoor-to-outdoor (I/O) ozone concentration ratio and the average occupied CO_2 concentration in permanent (a) and portable (b) classrooms. Classrooms from all sampling periods (n=48) are included.

A positive relationship was observed between I/O ozone and the fresh air exchange rate, AER_f, as shown in Figure B6. An increase of the AER_f corresponds to a greater flowrate of fresh air supply to an indoor space. Because a greater amount of fresh air helps to dilute and exhaust indoor pollutant levels, indoor CO_2 concentration and AER_f are inversely related.

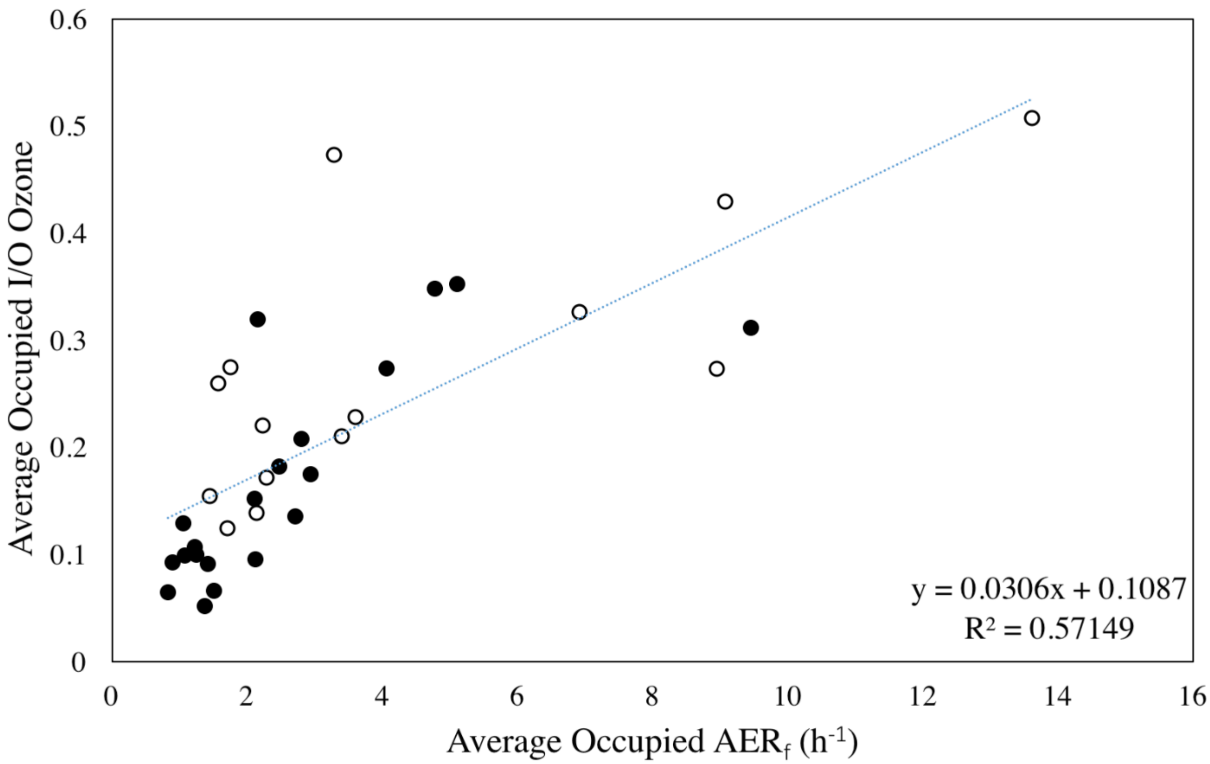

Figure B6: Scatter plot showing the relationship between the average occupied indoor-to-outdoor ozone concentration ratio (I/O) and the average fresh air exchange rate (AER_f, h^{-1}) during the occupied time in all sampling periods. Data from classrooms in which the AER_f was available (n=35) are included. Permanent classrooms are represented by closed data points, while portable classrooms are represented by open data points.

Discussion

The influence of the outdoor environment on the indoor environment is demonstrated by weekly concentration profiles presented in this study. Indoor ozone concentrations measured in most classrooms studied closely followed the same pattern as the outdoor ozone concentrations, indicating that the outdoor environment is the primary source of ozone in schools, i.e., as opposed to internal sources such as photocopy machines and laser printers. Indoor concentrations are typically lower than outdoor concentrations due to ozone reactions that take place in the heating, ventilating, and air conditioning (HVAC) systems and the classrooms themselves.

The importance of HVAC system operation on indoor ozone concentrations is supported by the premature peaking of indoor ozone concentrations prior to outdoor ozone peak occurrences. This premature peaking of indoor ozone concentrations typically happens immediately after each school day when mechanical systems are switched off. When the HVAC system is switched off, indoor ozone concentration rapidly decreases, regardless of the outdoor ozone concentration profile. This decrease occurs due to the dramatic reduction of fresh air supply to each classroom. The reduction of fresh air prevents additional ambient ozone from entering the classroom and allows indoor ozone more time to react with surfaces and airborne chemicals in the classrooms, further reducing its indoor concentration. Though outdoor ozone concentrations sometimes remain elevated throughout the late afternoon and early evening, the classrooms studied exhibited significantly lower ozone concentrations during these periods due to mechanical systems being switched off.

In portable classrooms, where the fresh air supplied by HVAC systems is supplemented by infiltration through the building envelope, the indoor ozone concentrations were typically higher than in permanent classrooms. Permanent buildings typically have tight building envelopes designed to prevent wasted energy that results from unconditioned air leaking into indoor spaces. Information from school utility managers about the operation of HVAC systems indicated that only the minimum amount of fresh air is supplied to each permanent classroom daily, regardless of outdoor temperature or weather patterns, specifically to reduce conditioning costs. Additionally, all permanent classrooms in the study had inoperable (unable to open) windows, making it impossible for occupants to supplement the fresh air supply through natural ventilation.

Alternatively, portable structures are built to be both temporary and inexpensive, and they often have building envelopes that are much "leakier" than their permanent building counterparts. The portable classrooms in this study have been shown to have leakier building envelopes, resulting in the infiltration of large amounts of unconditioned air on a daily basis (Lesnick et al., 2017). In fact, infiltration often served as the primary method of delivering fresh air to classrooms; in all but one of the portables studied, the fresh air intake damper was permanently and deliberately fixed in a closed position by maintenance staff (Lesnick et al., 2017).

Portable classrooms are directly accessible to the outdoor environment, which also increases the influence of occupant activities on indoor ozone concentrations. For example, if an occupant opens a window or door of a portable classroom, the room is immediately exposed to a large influx of ambient air. This effect provides occupants with a greater ability to control ventilation and temperature by opening doors or windows to bring in fresh air. In addition to the differences in construction and outdoor accessibility, the portable classrooms in this study were also serviced by different types of HVAC systems than permanent classrooms. All portable classrooms in this study employed single-zone wall air conditioning (AC) units. These units are smaller and less complex than the HVAC systems used in permanent buildings, where one permanent classroom may be connected to an HVAC system with twenty-five or more other classrooms and an adjoining hallway. The different types of HVAC systems and varying methods of operation can influence both the volume of fresh air received by a space and the length of time the fresh air is supplied.

Throughout all four sampling events, the ranges of average indoor-to-outdoor ozone concentrations (I/O) were relatively similar. The lowest I/O were nearly identical across sampling periods, ranging between 0.04 and 0.07. The highest I/O recorded in Fall 2015 (0.42) and Spring 2016 (0.37) were relatively close in value, although slightly higher I/O were recorded in Fall 2016 (0.51) and Spring 2017 (0.68). Some I/O values (25%) calculated for the schools in this study fall within the range of 0.3 – 0.7 reported for schools in Mexico City and Southern California (Weschler 2000). However, 75% of I/O values calculated for the schools in this study were lower than the range reported for schools in aforementioned studies. Because the studies in Mexico City and Southern California happened in 1992 and 1973 respectively, a difference in building technology is likely that cause of the discrepancy in I/O values. Since these studies were completed, tight building envelopes and other energy-saving measures have become standard practice in most buildings.

The relationship between I/O for ozone and carbon dioxide (CO_2) concentrations depends on both occupancy levels and magnitude of fresh air exchange rate. These two factors interact and influence one another, and it is likely that both work together to cause the relationship reported in this study. Increased supply of fresh air by HVAC systems influences both the CO_2 concentration and the I/O for ozone in a classroom. The supply of fresh air simultaneously decreases the concentrations of indoor-originating pollutants and increases the concentrations of outdoor-originating pollutants. As more fresh air is supplied to an indoor space, accumulated CO_2 is diluted and exhausted and indoor ozone has less time to react before more ambient ozone is delivered. Conversely, if less fresh air is supplied to an indoor space, CO_2 will continue to accumulate and indoor ozone will have a greater amount of time to react in the room, thus reducing its concentration An important surface that ozone will react with in occupied classrooms is the skin oils of students (Weschler, 2004; Weschler, 2006). As such, at the same air exchange rate, more students will lead to higher CO_2 and lower I/O for ozone

Conclusion

In this study, it was found that mechanical ventilation systems have a substantial influence on the indoor ozone concentrations in high school classrooms. Portable classrooms were found to have indoor ozone concentrations that were generally more variable than permanent classrooms.

A relationship between carbon dioxide (CO_2) and the indoor-to-outdoor ozone concentration ratio (I/O) was demonstrated when permanent and portable classrooms are considered separately. Portable classrooms were found to be more densely populated during school, which could have an effect on ozone reactions indoors and, consequently, the relationship between I/O ozone concentrations and CO_2. All portable classrooms also had identical mechanical ventilation systems and proximity to the outdoors, which could also have an effect on the relationship between I/O ozone concentration and CO_2. More research is necessary to determine the influence of occupant density and mechanical ventilation on indoor-to-outdoor concentration ratios for ozone.

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